A CONTRIBUTION

TO THE

HYDROGRAPHY OF THE NORTHERN NORTH SEA.

By

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P R E F A C E.

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I am indebted also to the Fishery Board for Scotland for accommodation in their Laboratory at Aberdeen, where the original data upon which the thesis is based are to be consulted, and I appreciate the opportunity afforded me of participating in a cruise of the Research Vessel "Explorer", during which I obtained an insight into the practical operations of hydrography. I have, moreover, to acknowledge the generous advice of the Board's Scientific Superintendent, Alexander Bowman, D.Sc., F.R.S.E., who supervised my work in the interests of the Carnegie Trust for the Universities of Scotland during my tenure of a Research Scholarship; and, finally, for my initiation into the methods of hydrographic research, and for his guidance throughout, I am particularly grateful to Mr. John B. Tait, B.Sc., Ph.D., F.R.S.E., Hydrographer on the Board's research staff.

R.M.

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T A B L E S.

INTRODUCTION.

General.

The Fishery Board for Scotland, through its Scientific Department, has been engaged in hydrographical and biological research in the Northern North Sea and its adjacent areas for the past thirty years, with an interval corresponding to the war period. Reports upon the hydrographic data collected during the years 1902-1910 inclusive have already appeared (1,5)* and these establish the water economy of the Northern North Sea to be broadly as follows.

Water whose physical characteristics denote Atlantic origin penetrates the North Sea from the north at all seasons of the year, but the volume and strength of this influx varies from season to season and from one year to another. Similarly, the seasonal spread over the surface of relatively fresh coastal water - principally that issuing from the Baltic area - is not of the same extent every year.

Within yearly periods, therefore, broadly similar conditions may be anticipated, and in addition to demonstrating this, the present study aims at a more particular examination of those differences which apparently distinguish one year from another.

Detailed comparisons of the data for a number of years are thus called for and since it is desired to continue the work of a year-to-year survey, the following research is applied to the four years 1911 to 1914.

Further,/

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* Red numerals refer to the bibliography, page 133

Further, the present study, based on temperature and salinity data, is intended to bear upon the information relative to surface currents which has been derived from surface drift-bottle experiments begun during the years in question.

The Data.

The complete data in original form and comprising several thousands of temperature and salinity observations are contained in the Station Observation Books carried by the research vessel. They are also to be found in tabular form, after due corrections have been applied to the temperature readings, in the Bulletin Hydrographique published by the International Council for the Exploration of the Sea. They are therefore not reproduced as tables in the present thesis but are contained in either sectional or temperature-salinity diagrams as explained below. The corr-:ections above referred to, and which were carefully scrutinised and checked are (i) in respect of instrumental error, and (ii) for adiabatic cooling effects upon water brought up from the greater depths.

Thereafter the entire data were transferred to specially prepared hydrographic cards, one card for each series of observ-:ations at a given position or "station". These cards were then filed on an 'index' basis which greatly facilitates the manipulation of, and reference to the material.

Methods.

The methods employed in the present survey are essentially those which are almost universally employed in this type of work, namely, the construction of vertical section diagrams and of hori-:zontal charts for various depths. In addition, a comparatively new method, employed for example by Jacobsen (2) and generally referred to as that of the temperature-salinity, or simply T-S diagram, is introduced for the first time in the treatment of Scottish data.

The Sections.

Vertical sections are constructed on millimetre-squared paper from series of stations lying approximately on a straight line and operated within narrow limits of time.

The choice of scales is governed by the following desiderata: (i) the clear illustration of detail, (ii) uniformity as far as possible among the numerous sections, and (iii) facility of con-:struction.

To meet these conditions the most convenient scales were found to be (a) a standard horizontal scale of 1 : 1,000,000 (i.e. 1 mm. = 1 Km.) and two vertical scales (b) for the deep waters of the Faroe-Shetland Channel and Southern Norwegian Sea of 1 : 5,000 (i.e. 1 mm. = 5 m.) and (c) for the remainder of the sections, which are mainly in the Northern North Sea area, a vertical scale of 1 : 2,500 (i.e. 1 mm. = 2.5 m.).

The difference between the horizontal and vertical scales gives,/

gives, of course, a distorted picture, which fact must always be borne in mind in reading from these diagrams. In the case of the deeper water sections, the depth is exaggerated 200 times in relation to the length, and in the shallower sections, 400 times.

The construction of isotherms and isohalines involves inter-:polation. Around a given point in a section, interpolation is performed, as far as possible, only with the observations immediately above and below and with those at the same depth at the nearest station on either side. That is to say, as a general rule, inter-:polations are made only in the vertical and horizontal directions. Cases, however, occur where the insufficiency of data allows of interpolation only in an oblique direction and while in the majority of cases this is permissible, instances arise where this operation would give a false trend to an isopleth.

To avoid the rather cumbersome method of referring to a station by its latitude and longitude and as such precision is seldom necess-:ary in the text, a more convenient, though less exact method of reference is adopted.

For statistical purposes mainly, the North Sea and its adjacent regions have been divided into rectangular areas whose sides are 1° of longitude and 30' of latitude. Any such rectangle is specified by quoting the letter heading the column and the number denoting the row in which it occurs. These rectangles are further sub-divided into four parts by joining the mid points of opposite sides, the quadrants being styled a, b, c, d (NW, NE, SW and SE respectively). Examples of this nomenclature are to be seen on Figure 2 etc. Thus a particular point, say lat. $59^{\circ}40'$N., long. $1^{\circ}14'$W. is referred to in the shorter notation as C18d. On the section diagrams, both specifications for each section are entered. Further, the full data for all stations embraced by the sections are given on these diagrams.

The/

The Horizontal Charts.

These charts are constructed wherever data are available to cover a sufficiently wide area and where the difference in time between the first and last observations can be disregarded without incurring undue liability to error on account of change of hydro-:graphic conditions in the interval.

Interpolation is again necessary in the construction of these diagrams. As in the case of the sectional diagrams, the assumption is made of uniform change of conditions along the straight line joining neighbouring stations, and further, interpolation round a point is effected only with those stations nearest to it and not more than about forty miles distant. The positions of all the stations employed in the construction of a chart are shown on it by small black circles.

In the present thesis the isopleths are drawn strictly from the data available. In a few cases where it was possible, observations other than those taken by the Scottish research vessel, but contained in the appropriate issue of the Bulletin Hydrographique, are utilised to extend the isopleths beyond the area embraced by the Scottish material. The likelihood of there being more or less close analogy between the hydrographic conditions of one period and those of another is in no case given effect in the construction or amplification of any of the horizontal charts.

The Temperature-Salinity or T-S diagrams.

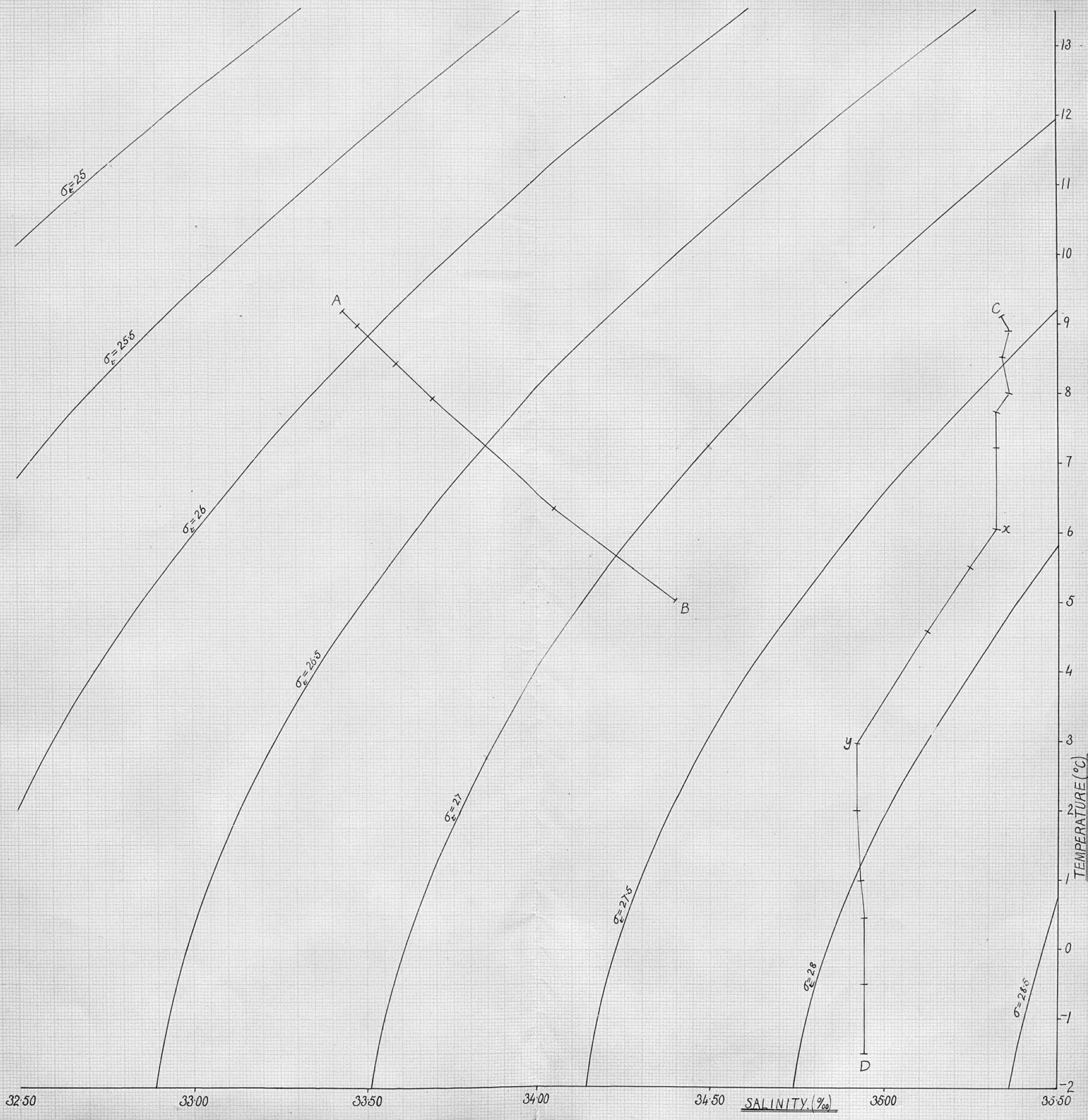
In the T-S diagrams, rectangular co-ordinates are utilised, the abscissae being salinities and the ordinates temperatures. Any point on this diagram, then, is compounded of temperature and salinity,

and/

F I G U R E   I.

TEMPERATURE-SALINITY

DIAGRAMS.



σt=25
σt=25·5
σt=26
σt=26·5
σt=27
σt=27·5
σt=28
σ=28·5
A
B
C
x
y
D
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
TEMPERATURE (°C)
32·50
33·00
33·50
34·00
34·50
35·00
35·50
SALINITY (‰)

and as these two factors together determine density, (σ_t) (calculated from Knudsen's Tables (4) or Sund's oceanographical slide-rule) all combinations of temperature and salinity for a given density can be plotted and the curves of equal density (isopicnals) drawn, for example $\sigma_t = 26$, $\sigma_t = 26.5$, etc. as shown on the sample T-S diagram, Figure I.

A T-S curve for any station is constructed by joining in order the points plotted from the temperature and salinity data for each of the depths from which observations were taken. The positions of these determining points on the curve are indicated by short transverse lines (depth-marks) as may be seen on Figure I.

Considerations of clarity alone impose limits to the number of curves which may be inserted on one T-S diagram.

The properties of these diagrams are as follows:-

(a) In the case of individual curves, the distribution of density throughout the water-column represented may be seen directly by reference to the isopicnals. The more nearly perpendicular a station curve is to the isopicnals, the greater the stability of the water at that station, while a small angle of intersection indicates relatively low stability. When the curve crosses the isopicnals towards lower densities with increase of depth, definite inversion of density is obvious. On Figure I curve AB exhibits high stability and section xy of CD very low stability.

(b) When a number of curves are plotted on one diagram, a point or points may exist through or near which many of the curves pass or upon and around which a large number of the transverse bars to the curves lie. This disposition indicates that water of similar salinity and temperature occurs at many stations. The co-ordinates of such a point give, therefore, the temperature and salinity of a water-type common to the stations whose grouping forms the point.

(c)/

(c) The straight line joining two such points indicating water-types is the locus of points representing water which is a product of mixing between these primary types. The relative amounts of the two parent types in any such mixture is inversely proportional to the displacement of the point representing this mixture from the extremities of the straight line. When two or more such points are known, curves may be examined for relationship to them, that is, an investigation may be made of the part played by known water-types in the composition of the water at chosen stations.

(d) General. The massing of all the data for a number of stations on one diagram, as is possible with the T-S diagram, allows of a comprehensive survey of temperature and salinity at all or particular depths - say, the bottom. Regional divisions within the area covered by the data may be revealed by the falling apart of the mass of curves into groups with common characteristics within each as to surface or bottom temperature or salinity, or general disposition of the curve, or some or all of these characteristics, though these common features may not be definite enough to specify water-types as in (b).

From the T-S diagrams may be found the data for the few stations not represented on one or other of the vertical sections.

Plan of the Thesis.

In the following pages there is a detailed examination of the hydrographic data as shown on the three types of diagrammatic aids. The four years constitute the main headings and in the case of 1911, 1912 and 1913 the total area covered is treated by regions - Faroe-Shetland Channel, Southern Norwegian Sea, Northern North Sea and Middle/

Middle North Sea. In 1914 the data are practically confined to the Northern North Sea.

The order in which the regions are dealt with results from the dependence of conditions in the North Sea on the influence or absence of influence of Atlantic water. It is desirable therefore to observe this water in the first place in its least diluted state, that is, in the Faroe-Shetland Channel. An examination of hydrographic conditions in the Southern Norwegian Sea follows naturally, on account of the function of this area as the gateway to the North Sea.

The Faroe-Shetland Channel is bounded arbitrarily on the north-east by a straight line from the north of Shetland to the north of Faroe, and in the south by a natural limit, the Wyville Thomson Ridge, which runs from off Cape Wrath to Faroe Bank (60 miles SW of Faroe) and has nowhere a greater depth of water on it than about 500 metres. (A bathymetric chart will be found in the front of the folder containing horizontal charts).

Off Orkney and Shetland the edge of the continental shelf is almost rectilinear in form from 59°N. 8°W. to 61°N. 2°W. Between this and the less regular but equally wide Faroe shelf the deep trough of the axis of the Channel reaches depths greater than 1000 metres.

The Southern Norwegian Sea region marches with the Faroe-Shetland Channel on the west and with the North Sea on the south, the latter boundary being taken to be the 61st parallel. Latitude 63°N. is the northern limit of the area for present purposes. The Southern Norwegian Sea covers part of the Scottish Continental Shelf, which reaches its most northerly point in a spur at 61°30'N. 2°E. and is separated from Norway by the deep trench which flanks the coast of that country from the Skagerak to 62°N. Northwards from the Shelf the bottom drops into the deeps of the Norwegian Sea.

The/

The Northern North Sea is defined on the south by lat. 57°30'N and is broadly that part of the North Sea with depths between 50 and 60 fathoms. On the east, the deep Norwegian trench bounds the comparatively level plain of the Northern North Sea, whose only important eminence is the Viking Bank, which occupies a position between 60°30'N. - 61°N. and 2° - 3°E. and rises to within 40 fathoms or less of the surface.

The Middle North Sea lies south of lat. 57°30'N. and in contrast to the Northern North Sea is of less than 50 fathoms depth, except in the Gut, a shallow trench which extends south along longitude 1°E. to 56°N. At 57°N. 4°E. the Fisher Bank is less than 30 fathoms below the surface.

For each of the above areas the hydrographic data are examined first with the aid of vertical sections, then with horizontal charts and finally with T-S diagrams. The first of the above graphical representations is the most detailed, the second shows the broader aspect and the third, in determining water-types and their relation-:ships, sums up hydrographic conditions.

The year 1911 is dealt with at greatest length. In the analysis of the hydrographic data for that year there are incorporated a number of tables which afford a basis for comparing hydrographic conditions in 1911 with those in the series of years 1902-1910. The material for these tables is derived from the data and diagrams published in Helland-Hansen's (1) and Robertson's (5) reports. Such important features of the hydrography as the cross-sectional area of Atlantic water on the same two vertical sections in the Faroe-Shetland Channel, maximum salinities etc. are tabulated for each of the years for which data are available. A background is thus provided against which hydrographic conditions in the years 1911/

1911-1914 appear in their true perspective.

Following the year-to-year survey is a discussion of the area as a whole, pointing out what are considered to be the salient features of the hydrography and the characteristics peculiar to each of the four years. The principal points in which the present thesis claims to amplify or modify previous work in the same areas are also indicated.

GUIDE TO THE CONSULTATION OF DIAGRAMS.

For ease of reference the three different types of diagrams are bound in separate folders, within each of which the diagrams are arranged in groups according to year - 1911, 1912, 1913 and 1914.

Instead of a simple consecutive numbering of all the diagrams, a system of notation has been adopted which, in addition to making location easy, has the advantage that when a diagram is referred to in the text it is at once apparent to what type and year it belongs, without further note to that effect being required.

A diagram is referred to thus:-

VS(11)17 HC(12)4 TS(14)3

The initial letters indicate the type of diagram - VS signifies vertical section, HC horizontal chart and TS temperature-salinity diagram. The bracketed figures refer to the year and the final element is the serial number of the diagram of the type and year specified.

The contents of each page in the folders are given in this notation in a green frame in the top right-hand corner of the sheet.

THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS

DURING THE YEAR 1911.

THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS DURING THE YEAR 1911.

THE FAROE-SHETLAND CHANNEL.

In 1911 this area was visited, first, between the 9th and 16th of May, when approximately the same two parallel lines of hydrographic stations as were traversed from time to time in earlier years (1 & 5) were again laid down in the northern part of the area between the Shetland and Faroe Islands. These two lines, as worked in May 1911, are numbered 1 and 2 (in red) on Figure 2, the stations on each line being denoted by small circles and numbered, for reference purposes, according to the convention explained in the Introduction p. *viii* In addition, there are in the southern part of the Channel and extending southwards into the area west of the Outer Hebrides, other two lines of stations (Nos. 3 and 4, Figure 2) pertaining to the month of August. A further four stations, also for August, complete the Scottish Faroe-Shetland Channel data for the year. Two of these stations were situated some 20 miles westwards of the Mainland of Orkney and the other two between the island of Foula and Shetland.

Conditions in May 1911.

S a l i n i t y.

Diagrams VS(11) 1 and 2 are the vertical sections constructed from the temperature and salinity data of the two lines of stations worked during this month. Each line comprises seven stations.

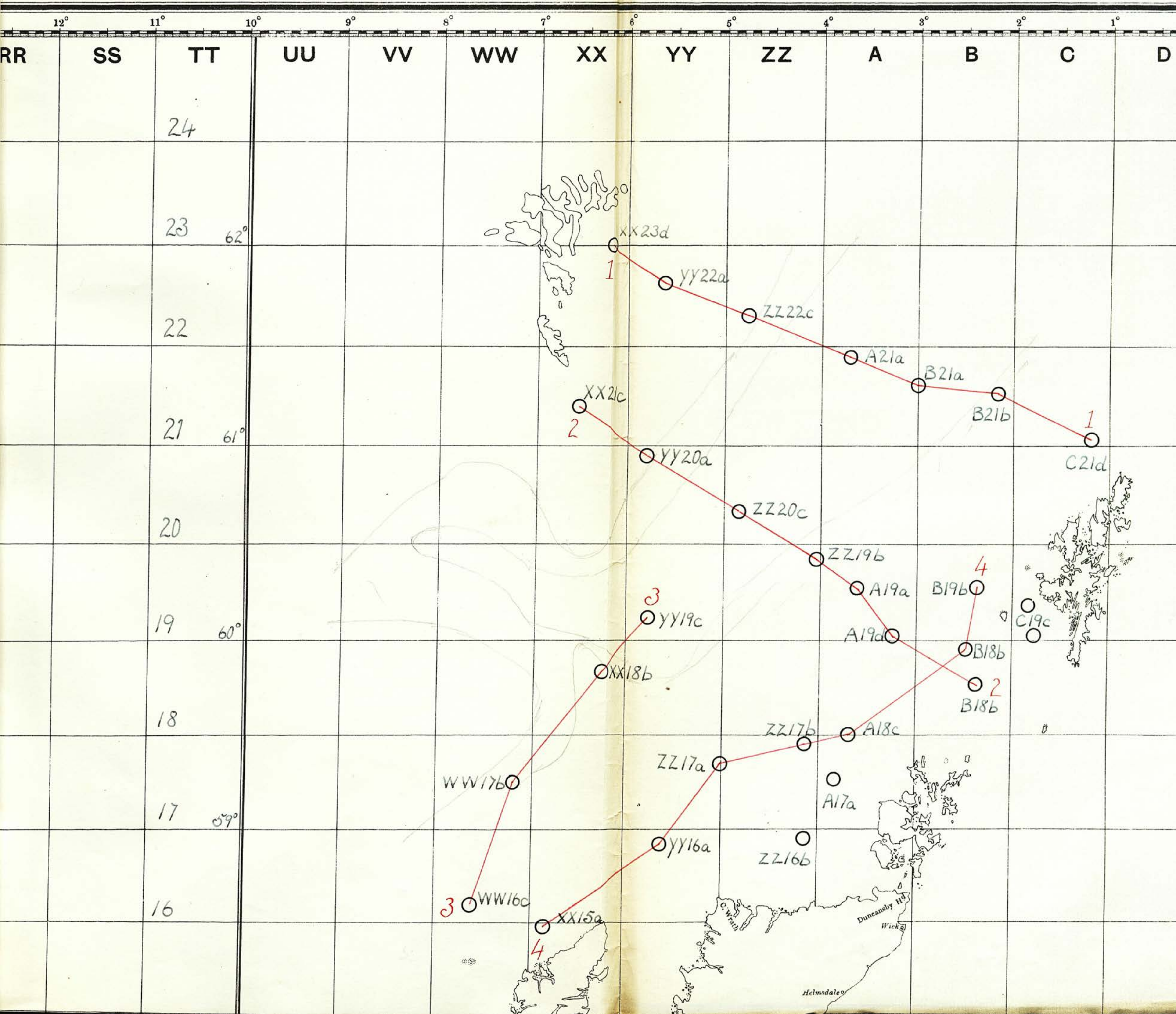
The principal feature of the Faroe-Shetland Channel region, in relation to Northern North Sea hydrography, is the warm salt water of Atlantic origin to be found there at all times of the year. Its consideration, therefore, forms a convenient starting-point in the present study. As has previously been done by Helland-Hansen and Robertson (1 & 5), salinities of 35.25°/oo and/

FIGURE 2.

FIGURE 2.

POSITIONS OF SECTIONS

FAROE-SHETLAND CHANNEL, 1911



and over, may, in the first instance, be regarded as belonging to practically undiluted Atlantic water. The 35.25 $^{0}/_{oo}$ isohaline may thus be taken as defining the limits of the main Atlantic influence in the Channel. Water of the above characteristics was, in greatest bulk, confined to the eastern side of the northern part of the Channel in May 1911, as shown on VS(11) 1 and 2. The above-mentioned authorities have indeed found this to be almost always the case in this area.

The cross-sectional areas of Atlantic water on the two hydrographic sections for May 1911 are approximately 57Km^2 on the northern section and 60 Km^2 on the southern.* The following table relates these figures to the corresponding areas for those years in which practically the same sections were worked in the same season. The measurements are taken from Helland-Hansen's and Robertson's diagrams accompanying their reports already referred to.

TABLE I.

Cross-Sectional Areas of Atlantic Water (salinity over 35.25$^{0}/_{oo}$) in Spring on Two Parallel Hydrographic Sections between Shetland and Faroe.

Month, Year	Northern Section Km^2	Southern Section Km^2
May 1903	27	32
" 1904	82	63
June 1905	81	49
" 1906	11	44
April 1908	14	29
" 1909	68	77
June 1909	12	45
May 1910	4	14
" 1911	57	60

It can at once be inferred from the above table that the volume of Atlantic water present in the northern part of the Faroe-Shetland Channel in spring or early summer is not even approximately the same in all years. From the circumstances however (i) that the Atlantic water in/

* Areas are measured by planimeter throughout.

in this region is carried by, and indeed comprises, a current flowing in general direction north-eastwards from the Wyville-Thomson Ridge towards the north-west Shetland area and (ii) that the sections lie at no great distance apart (60-70 miles) it might be expected that almost equal cross-sectional areas of Atlantic water would be found on both sections, or alternatively, that the area would be greater on the southern section than on the northern. The latter condition appears to be more generally true, for, with due allowance for the approximation of the diagrams as representative of actual conditions, in only two, or at most three, of the eight years specified in Table I can the amounts of Atlantic water on the two sections be said to approach equality, namely, in the years 1903 and 1911, and perhaps also in 1909 (April). It is to be observed, however, that even in these instances the tendency is for the Atlantic water on the southern section to be in excess of that on the northern. This, as already indicated, is much more definitely the case in the majority of the remaining entries of the table, notably as regards June 1906, April 1908, June 1909 and May 1910. In passing, the profound differences between the sections for April and June 1909 should be noted, as indicative of the magnitude and rapidity of the hydrographic changes which can take place in the region in a comparatively short interval of time.

In May 1904, and again in June 1905, the northern section plainly carried the greater amount of Atlantic water, as defined by salinities in excess of $35.25^{\circ}/oo$. In these years, too, the volume of Atlantic water in the northern part of the Channel in spring would seem to have been maximal, on the assumption that the sum of the northern and southern cross-sectional areas for each of the months tabulated is directly related to the volume of Atlantic water in the area. This condition, however, cannot be said to be characteristic only of those years in which the northerly section carried more Atlantic water than the southerly one, for, on the same assumption, Table I shows that the amount of Atlantic water present/

present in April 1909 was probably much the same as in May 1904, and further, that May 1911 does not fall far short of June 1905 in this respect. In both April 1909 and May 1911, the area of Atlantic water on the northern section was apparently somewhat <u>less</u> than on the southern.

From the data of Table I, then, it is reasonable to infer that the Atlantic influence in the northern part of the Faroe-Shetland Channel in the spring of 1911 was comparatively great, approaching, in fact, maximal conditions as these are represented by the observations pertaining to the same season of the years 1904, 1905 and 1909.

As a further measure of Atlantic influence in the area under discussion, the maximum salinity recorded for each of the sections dealt with in Table I may be considered.

TABLE II.

Occurrence of Maximum Salinity on Two Parallel Hydrographic Sections in the Faroe-Shetland Channel in Spring.

Month, Year		Northern Section			Southern Section		
		Maximum Salinity (°/oo)	Station	Depth (metres)	Maximum Salinity (°/oo)	Station	Depth (metres)
May	1903	35.47	B21b	0	35.38	A19c	0
May	1904	35.39	C21d	0	35.39	ZZ20c	0
			B21a	0			
June	1905	35.39	B21b	0-150	35.41	XX21c	0
June	1906	35.26	C21d	0-100	35.37	ZZ19b	0-20
			B21b	0-100			
April	1908	35.32	B21b	0-10	35.30	A19a	0
			B21a	0			
April	1909	35.39	B21b	0	35.35	YY20a	30-100
						ZZ20c	0
						ZZ19b	300-330
June	1909	35.26	A21a	10-70	35.34	ZZ19b	0-300
						A19a	10-100
May	1910	35.30	B21b	10	35.37	ZZ20c	0
			B21a	20			
May	1911	35.52	B21b	50	35.35	A19d	20

It appears that spring salinities in the Faroe-Shetland Channel area north of about Lat.60°N. seldom exceed 35.40°/oo. In the above table, only three/

three such excesses are noted, the highest value, $35.52^{0}/oo$, occurring on the northern section in May 1911. This is followed by the value of $35.47^{0}/oo$, also on the northern section, in May 1903. The third record, however ($35.41^{0}/oo$), belongs to the southern section of June 1905, which, with May 1911, is one of the four spring seasons of maximal Atlantic influence. The other two maximal seasons, May 1904 and April 1909, register the same salinity maxima of $35.39^{0}/oo$, which is equalled by no further entry of the table.

On the other hand, the lowest maxima occur in June 1906, April 1908, June 1909 and May 1910 - in just those four years, when, according to the assumption already stated, the amount of Atlantic water present was minimal.

With May 1903 as an exception, therefore, it would appear that the highest spring salinities are to be expected in those years when Atlantic water bulks largest in the area.

Now, the southern hydrographic section, lying nearer, as it were, to the source of the Atlantic water, and generally showing a greater cross-sectional area of this type than the northern section, might also be expected to show more often than the latter the maximum salinity for the area. Of the nine entries in Table II, however, four show the maximum in the north and four in the south. In the remaining entry the same value is reached on both sections.

The positions of the stations at which the maximal salinities occur is worthy of investigation, for no doubt these values are closely associated with the nucleus of the Atlantic stream through the Faroe-Shetland Channel. The following table gives the frequency-distribution of maximum salinity in spring at the several stations in order from west to east on both sections.

TABLE.

TABLE III.

Frequency-Distribution of Maximum Salinity on Two Parallel Hydrographic Sections in the Faroe-Shetland Channel in Spring.

Northern Section	Station	XX23d	YY22a	ZZ22c	A21a	B21a	B21b	C21d
	Frequency	0	0	0	1	3	7	2
Southern Section	Station	XX21c	YY20a	ZZ20c	ZZ19b	A19a	A19d	B18b
	Frequency	1	1	3	3	3	1	0

B21b is clearly the mean position of the nucleus of Atlantic water on the northern section. The nucleus on the southern section is apparently to be found with equal frequency at the three stations ZZ20c, ZZ19b and A19a, that is, it is not so constant in position as on the northern section. If, however, ZZ19b be taken as the mean position on the southern section, the straight line drawn from it to B21b may be regarded as defining the approximate mean position of the axis of the Atlantic stream in this part of the Channel in the spring of the year. The axis then appears as a SW⟶NE line from Lat. 60°30'N. Long. 4°W. to Lat. 61°30'N. Long. 2°W., running parallel to the 100-fathom bathymetric contour and about 20 miles west of it.

The occurrence of maximum salinity at the two westmost stations on the southern section is to be noted. At XX21c, the station nearest to Faroe, the high maximum of 35.41°/oo was recorded at the surface in June 1905. This, however, is practically an isolated observation, for at a depth of only 10 metres at the same station, the salinity had fallen to 35.26°/oo, and at no greater depth was even this value attained. Moreover, between this high surface salinity and the next highest one of 35.39°/oo at station A19a, three stations intervened at which the surface salinities were 35.37°/oo and less.

The maximum salinity at YY20a refers to April 1909, when however, the same maximum was registered also at ZZ20c and ZZ19b, two of the three stations on the southern section showing the greatest frequency of maximum salinity.

Hence,/

Hence, though these considerations show that the distribution of maximum salinities on the southern section is less scattered than appears at first sight from Table III, the fact remains that the nucleus of the Atlantic water is more variable in position on the southern section than on the northern, where it is more definitely confined to the eastern side of the Channel. This difference suggests that some agency may be at work in the north-west of the Channel, restricting the Atlantic water to the Shetland side. It will be seen later that such a force does indeed exist.

With regard to the depths at which maximum salinities occur, Table II reveals that, though generally observed at the surface, this is not invariably, nor, even at those stations where it does happen, is it exclusively the case. May 1911, however, is unique in having only one maximum observation at a point well below the surface on each of the two sections. These occur at 50 metres and 20 metres respectively on the northern and southern sections.

Sometimes maximum salinity extends over more than one station on the section, and, at a given station, to considerable depths from the surface. At other times, the maximum commences only at some point below the surface, and may extend downwards for 30 to 100 metres. Nevertheless, the normal position vertically for the nucleus of the Atlantic stream, as indicated by maximum salinities, appears generally to be in the surface layer or layers.

In regard to May 1911 this is well illustrated by the diagram VS(11)1, where in the uppermost 100 metres on the northern section, no fewer than three distinct nuclei of Atlantic water, with salinities in excess of $35.35\,^{o}/oo$ are shown. Four nuclei, in fact, appear on the diagram, but two of these are registered at the same station, B21b, and are separated by the single observation of $35.28\,^{o}/oo$ at 20 metres, that is, by a matter of only eight to ten metres. The separation, however, appears to be quite genuine,/

genuine, as suggested by the salinity in the upper layers at the next station to the westward, namely B21a.

A similar breaking-up, as it were, of the main Atlantic stream is not indicated on the southern section, where conditions within the main body of water of salinity greater than 35.30 $^{0}/_{00}$ were obviously more uniform. Eddy-motion such as Helland-Hansen (1) considered likely and which hydrodynamical calculations have shown to exist in 1924 (3) is strongly indicated on the northern section.

The Atlantic stream in the Faroe-Shetland Channel possesses yet another feature, a consideration of which affords further opportunity for effective comparisons of May 1911 with the corresponding seasons of earlier years. This is the maximum depth attained by the stream in the northern part of the Channel. It can be seen from VS(11) 1 and 2 that the Atlantic stream as bounded by the 35.25 $^{0}/_{00}$ isohaline reaches a maximum depth of about 550 metres on both sections. This great depth is equalled only by that attained on the southern section in April 1909 and surpassed only by the maximum sounding of 600 metres of Atlantic water on the southern section of June 1906 . Apart from these records, maximal depths of even 500 metres, approximately, are recorded on two occasions, May 1904 (both sections) and June 1905 (northern section). It is to be noted that with the exception of 1906, the years specified are those which, from other considerations based on Table I, registered maximal volumes of Atlantic water in the northern Channel area.

Now the maximum depth of the Atlantic stream in the Faroe-Shetland Channel is related primarily to the mean depth of water on the Wyville Thomson Ridge. This latter depth is approximately 500 metres, which should therefore mark the bottom limit of the Atlantic stream at least for some distance after it crosses the Ridge. Farther north, that is, in the area with which we are immediately concerned, it is to be expected that/

that under ordinary circumstances, the mean maximum depth of the stream may be somewhat less than 500 metres, this because of the dilution of the underside of the stream with the fresher water, which, as will be indicated below, pervades the deep trough of the Channel.

There are three possible explanations of the sounding of over 500 metres of Atlantic water in the area in question, as in May 1911. First, by reason of its greater density the Atlantic stream may gradually and bodily sink while proceeding northwards. Secondly, opposing horizontal forces acting normally to the direction of the stream would, by con-:stricting the stream laterally, force it to sound greater depths. Two such opposing forces which must be effective at all times are (i) that due to the earth's rotation, tending to swing the stream round and bank it up against the Continental Shelf and (ii) the reactionary force due to the shelf itself. Thirdly, its greater density combined with unusual bulk may, under the action of gravity, be responsible for the abnormal depth to which the Atlantic stream sometimes attains. This third possibility appears to explain the conditions of May 1911, as also those of May 1904 and June 1905, in all three of which the amount of Atlantic water present in the northern part of the Channel was unusually great.

In addition to the forces cited above, there are evidences in May 1911 of other influences tending to restrict the lateral extension of the Atlantic stream in the Faroe-Shetland Channel. On both sections, VS(11) 1 and 2, there is a falling-off from the high Atlantic salinities to those which clearly indicate the presence of fresher waters on both sides of the stream.

Surface drift-bottle experiments (6) lead to the inference that the fresher water found in the area east of Faroe comes from the north and is probably associated to some extent with the East Icelandic Polar current. The movement off Faroe thus appears to be southerly, despite the fact that salinities are higher at the westmost station, XX23d, of the more northerly section than at the corresponding position further south (XX21c). As will be seen from the diagrams VS(11) 1 and 2

however/

however, temperatures are lower in the north than in the south in this region. The homogeneity of the water-column at the westmost station of both sections is worthy of note as suggestive of stable conditions, which are broken at the next station eastward in each case - YY22a and YY20a, by reason doubtless of the interactions of two distinct water-types, the Atlantic and the Norwegian Sea, or modified East Icelandic types. The courses of the isohalines, on VS(11)1 particularly, suggest that the fresh influence is impinging upon the Atlantic stream and restraining its westward spread.

On the eastern side of the Atlantic stream, there is not the same distinct indication of freshening influences on both sections as is the case on the west side. On the northern section it is to be noted that there is an interval of seven days between the observations at stations B21b and C21d, which may account for all or part of the differences between the salinities recorded at these two positions. But it is also to be observed that salinities at C21d are practically the same as those at A19d on the southern section, a similarity which suggests a current connection between these two stations. This is discussed below. The fresher water influence on the east side of the Atlantic stream is, however, quite clearly shown on the southern section, VS(11)2. There can be no gainsaying the significance of the homohaline water column at station A19d. Here again surface drift-bottle results are helpful in assigning the immediate origin of this fresher water at station B18b. Tait (6) has shown that the Orkney Islands as a group may be encompassed by an anticyclonic system of water movement, which derives its impetus from the west and south-west. Fresh water from the west Scottish coast and Hebrides region flows northwards, until, about Lat. 58°30'N. it is deflected by the Atlantic stream and appears not to reach higher latitudes than about 59°45'N. where its general direction of flow is eastwards towards the Scotland-Shetland passages/

passages into the North Sea. Hydrodynamical calculations (3) showed that in 1924 north-west coast water was actually entering the North Sea by these passages. Under these circumstances, therefore, its northern boundary in May 1911 would pass between stations A19d and B18b. In the same region the northern limit of the fresher water marks the southern boundary of the salter Atlantic water, but whereas the fresher water continues to swing round to the east, south-east and ultimately south, flowing between Fair Isle and Orkney, the Atlantic water on the other hand, in its approach to the opening between Fair Isle and Shetland, may turn off northwards and pass along the west side of Shetland. The above-noted similarity in the conditions at stations A19d and C21d in May 1911 corroborates in respect of that particular season this finding from drift-bottle results.

From the consideration of the fresher waters flanking the Atlantic stream in the Faroe-Shetland Channel we pass to that of the fresher water beneath it.

At practically all times, as stated by Robertson (5e, p.352) the deep trough of the Channel is occupied by water with a mean salinity of 34.92^{0}/oo, which characteristic, coupled with its low temperature, bespeaks its origin as being the deeper parts of the Norwegian Sea. Between the two water-types in the Channel there is a zone of mixing characterised by salinities of between 34.92^{0}/oo and 35.25^{0}/oo. The upper surface of the cold bottom layer is generally convex, so that its depth below the sea surface varies from point to point in the Channel. Moreover, this convexity allows of the upper surface of the bottom water being at a less depth than the maximum reached by the Atlantic water. This may be seen in many cases in Helland-Hansen's and Robertson's diagrams. The condition holds for May 1911, when, on the northern section, 34.92^{0}/oo water first appears at 500 metres at station A21a. Thereunder salinity at this station is uniform at 34.96^{0}/oo. At the adjacent station B21a, however, the salinity of the bottom water is

distinctly/

distinctly less.

On the southern section on the other hand the salinity of the bottom water nowhere falls below 35.01^{0}/oo. With the exception of a 35.03^{0}/oo recorded in August 1903, this value is higher than any found at the same great depth in the Faroe-Shetland Channel on any of the nineteen occasions between 1902 and 1910 on which the usual two lines of stations were traversed. This high salinity in the deep trough of the Channel in May 1911 is undoubtedly due to the penetration of some Atlantic water to these depths, a condition which, in view of the unusually large amount of Atlantic water present in the area at that time, is not surprising.

T e m p e r a t u r e.

As is to be anticipated by reason of its southerly origin, the Atlantic stream in the Faroe-Shetland Channel comprises the warmest water in that area. Temperature, however, is on the whole more sensit-:ive than salinity to modifying influences and therefore where these influences are present, as in the upper layers of the Faroe-Shetland Channel, temperature does not afford such a reliable guide to the differentiation of water types as does salinity. At greater depths in the Channel, however, a given salinity is generally found to be associated more or less with a particular temperature. For instance, the 35.25^{0}/oo isohaline, which defines, in section, the undersurface of the Atlantic stream, is usually followed closely by the 7^{0} and/or 8^{0}C. isotherms. The table below gives the temperatures linked with the 35.25^{0}/oo and 35.00^{0}/oo isohalines in the spring months between 1903 and 1910.

TABLE.

TABLE IV.

Correlation of Temperature with Salinities of 35.25°/oo and 35.00°/oo in the Faroe-Shetland Channel in the spring months of 1903-1910.

Month, Year	Northern Section		Southern Section	
	S = 35.25°/oo	S = 35.00°/oo	S = 35.25°/oo	S = 35.00°/oo
May 1903	8°	4°/5°	7°/8°	4°
" 1904	7°-*	4°	7°-	3°/4°
June 1905	7°	4°	7°/8°	3°/4°
" 1906	7°	4°	7°/8°	3°/4°
April 1908	7°-	5°	8°-	5°/6°
" 1909	7°-	3°-	7°-	3°
June 1909	—	4°	7°-	3°
May 1910	—	5°	—	3°

* minus sign

It is evident that, on the northern section, the 35.25°/oo isohaline is generally associated with the isotherm of 7°C., and on the southern section with, on the whole, somewhat higher temperatures - between 7° and 8°C. On the other hand, the 35.00°/oo isohaline is accompanied as a rule by temperatures of rather <u>more</u> than 4°C. on the northern section and rather <u>less</u> than 4°C. on the southern. That is to say, the undersurface of the Atlantic water is generally cooled and the upper surface of the bottom water warmed in the interval of 60 to 70 miles between the two sections.

In the light of the foregoing, the thermal conditions in the northern part of the Faroe-Shetland Channel in May 1911 may be considered. On the northern section, a maximum temperature of 9.13°C. is recorded at a depth of 10 metres at station C21d, which, it is to be observed, is situated outwith the region of maximum salinity. The station, however, is definitely within the Atlantic stream as defined by salinities greater than 35.25°/oo, so that the tempeatures exceeding 9° at C21d are also to be regarded as of Atlantic origin, as indeed is borne out by reference to the southern section where such temperatures are clearly associated with the higher Atlantic salinities. The maximum temperature of the southern section, 9.41°/

9.41°C., is registered at a depth of 10 metres.

Here, then, in the northern section of May 1911 is a case where highest salinities are not accompanied by highest temperatures. The influence which can be taken as the cause of the lowering of temperature between the southern and northern sections is one which, on account of its fresher nature, should also tend to the lowering of salinity in the Atlantic stream. This, as already pointed out, takes place only on a very small scale and in more or less isolated patches of the surface layer of Atlantic water. On the scale of units employed, accordingly, temperature, in the Faroe-Shetland Channel at least, is more easily affected by modifying influences than salinity, and is therefore less suitable, independently, as an index either of the quantity or of the exact locus of a definite water-type.

In lower layers, however, as remarked above, the case is different. In the northern section of May 1911 the same relationships hold between temperatures and salinities as are demonstrated by Table IV, that is, the $35.25^{\circ}/oo$ isohaline is coupled with the 7° isotherm, and the $35.00^{\circ}/oo$ isohaline with temperatures of 3° to 5°C. The association of the $35.25^{\circ}/oo$ isohaline and the 7° and 8° isotherms, generally characteristic of the southern Faroe-Shetland Channel section, again holds in respect of May 1911, but the correlation is with 8° rather than with 7°. Thereafter, however, the analogy of former years breaks down, for the reason that, as already indicated, no water of salinity less than $35.01^{\circ}/oo$ appears in the deeper parts of the southern section of May 1911.

Westwards of the Atlantic stream, temperatures fall to between 6° and 7° in the fresher water east of Faroe, and on the south-eastern flank, that is, at station B18b, to between 7.49° and 7.86°C. In both cases the small range of temperature, as well as the accompanying uniformity of salinity, is further evidence in support of the definition of distinct water-types in these areas.

As/

As regards the bottom water of the Channel in the spring of 1911, zero temperatures and below, to -0.86° C., are registered on the northern section. These are characteristic, in like case to the salinities at these depths. On the southern section, however, the singularity of the abnormally high salinities is coupled with correspondingly high temperatures - nowhere less than 2° C, which again points to the conclusion that, no doubt by reason of its extraordinary bulk in this year, 1911, Atlantic water invaded these great depths and mixed with the water which usually bears the distinctive physical features of deep Norwegian Sea water. The only previously-recorded case in the Scottish records of similarly high temperatures in the trough of the Channel is for August 1903, when, at 1000 m. at ZZ21c, the unusually salt ($35.03^{\circ}/oo$) water had a temperature of 1.71° C.

The main inferences and conclusions drawn from the foregoing detailed examination of the Faroe-Shetland Channel data for May 1911 may now be referred to horizontal charts constructed from the same material and depicting conditions on various horizontal planes.

Charts HC(11)1-5 illustrate temperature and salinity distributions at the surface and at depths of 20 m, 50 m., 100 m. and 200 m. respectively. The area covered by these charts extends into the Norwegian and North Seas but attention is confined meantime to the Faroe-Shetland Channel.

At the several depths, the axis of the Atlantic stream is clearly to be traced along the SE side of the Channel, following the edge of the Continental shelf round the north of Shetland. As far as the available data show, there is no indication that Atlantic water enters the North Sea between Orkney and Shetland.

Except on the plane of 50 m., where the high salinity at B21d is dominant, the Atlantic stream is wider in the southern part of the area covered by the data than on the northern.

At the surface, 20 m. and 100 m. there appears to be a southward push of/

of fresher water along 3° W., flanked by a thrust northwards of Atlantic water immediately to the west of it. This branching of the Atlantic stream is doubtless due to the impinging on its flank of the fresher water from the north. The southward-moving water would, by reducing the high salinities of the Atlantic stream, account for some at least of the reduction in width of the latter while passing through the Channel. At the meeting-place of the southerly current and the Atlantic stream, the result of the opposing motions will be eddying. Such gyrations have already been inferred from the discontinuity of the high salinity water on the northern line of stations.

Hydrographic conditions in the Faroe-Shetland Channel in May 1911 are finally summed up in the rectangular co-ordinate diagrams TS(11) 1 and 1a. The mode of construction and the uses of these T-S diagrams as they are styled, and in which temperatures and salinities are repre-:sented and treated conjointly, are explained in the Introduction p. ix

The superposition of TS(11)1a on TS(11)1 reveals at once a very close association among all the T-S curves for May 1911, such that, viewed collectively, they comprise almost a "family" of curves. As will be seen later, this grouping of the May station curves is in marked con-:trast to the arrangement of the Faroe-Shetland Channel T-S curves for August 1911.

Within the so-called family of curves, three concentrations of points or depth-marks are to be distinguished; (a) between salinities of $35.25^{\circ}/oo$ and $35.35^{\circ}/oo$ and temperatures of 8°-9.5°C; (b) within the rectangle formed by salinities of $35.15^{\circ}/oo$ and $35.20^{\circ}/oo$ and temperatures of 6°-7°C, and (c) round a mean salinity of $34.92^{\circ}/oo$, with a minimum temperature of -1°C. and an upper limit of 2°-3°C.

The first or uppermost of these concentrations represents water of characteristic Atlantic type. The points within this (a) group belong to two kinds of curves, one of which falls almost entirely within the salinity and temperature limits of the group. In the other kind, the

lower/

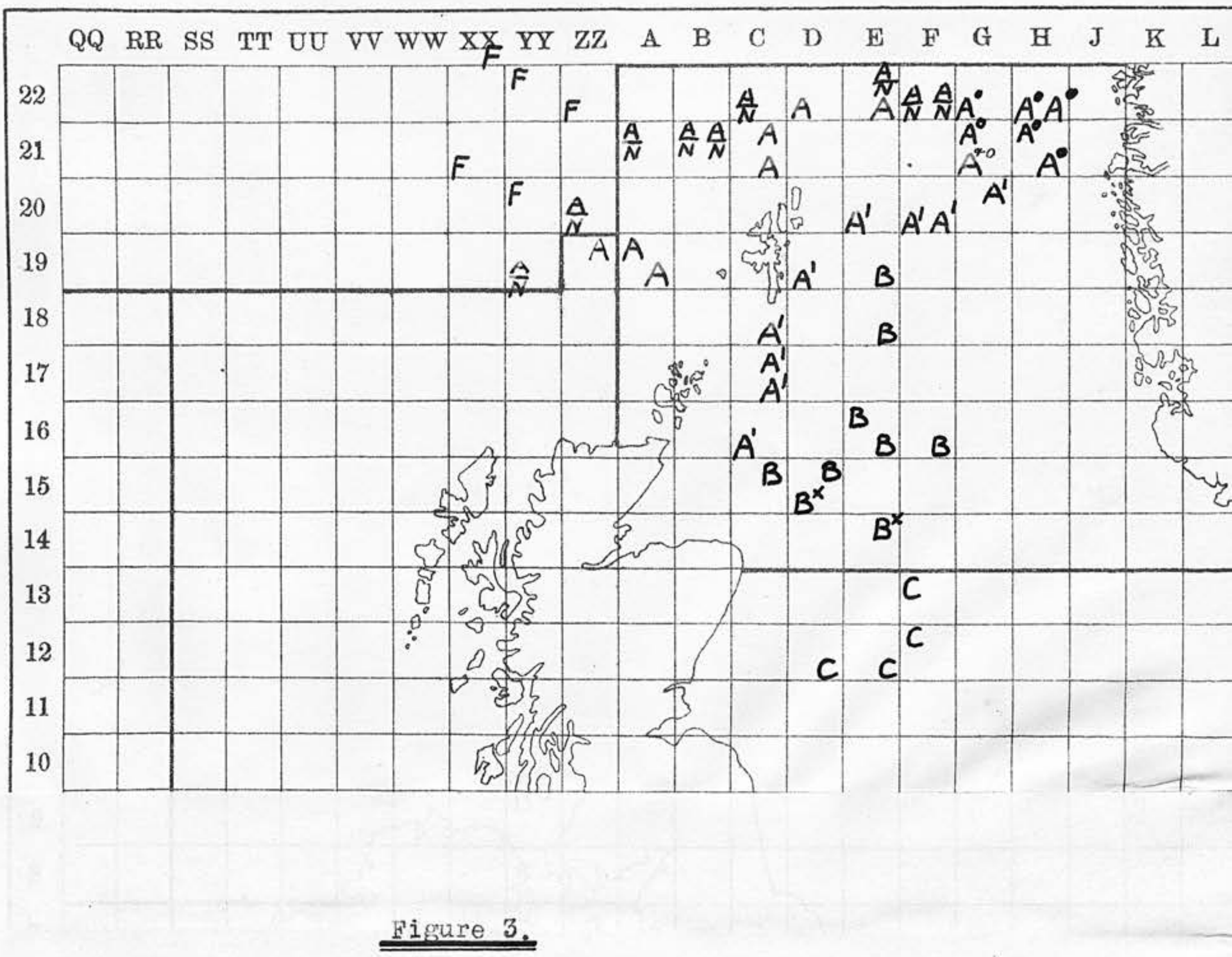


Figure 3.

Distribution of Water-types, May 1911.

Salinity and temperature of the water-types shown on Figure 3 together with the positions and dates of the stations whose T-S curves make up the groupings which represent the above types.

A_0
(35.25-.35 °/oo x 8-9°C)

TS(11)1

12	ZZ19b	13/5
17	A19a	13/5
18	A19d	13/5
27	C21d	16/5

TS(11)2a

2	C21b	11/8
3	C21d	11/8
4	D22c	17/5
5	E22d	17/5
7	G21c	18/5

$\frac{A}{N}$

TS(11)1

7	YY19c	23/8
11	ZZ20c	12/5
16	A21a	10/5
22	B21a	9/5
23	B21b	9/5

TS(11)2

7	E22b	23/5
8	F22c	23/5
9	22d	23/5

TS(11)2a

1	C22c	17/5

F_0
(35.15-.20 °/oo x 6-7°C)

TS(11)1a

2	XX23d	11/5
3	XX21c	12/5
5	YY22a	11/5
6	YY20a	12/5
10	ZZ22c	11/5

B_0
(35.00-.10 °/oo x5.75-6.5°C)

TS(11)4

10	C15b	23/5
18	D15b	24/5
×20	D15c	20/5
22	E19d	19/5
23	E18d	19/5
24	E16a	19/5
26	E16d	24/5
×27	E14b	24/5
30	F16d	24/5

C
(34.85-35.00 °/oo x 6-6.75°C)

TS(11)6

16	D12d	25/5
21	E12d	25/5
23	F13a	24/5
25	F12a	25/5

A'
(35.20-.30 °/oo x 6.5-7.5°C)

TS(11)4

×2	C18d	5/5
×4	C17b	5/5
×6	C17d	5/5
8	C16c	5/5
×15	D19c	5/5
21	E20c	19/5
28	F20c	19/5
29	F20d	19/5
31	G20b	19/5

A^0
(surface fresh, bottom cold)

TS(11)2

10	G21a	23/5
11	H21a	23/5
12	H21d	23/5

TS(11)2a

6	G22c	17/5
7	G21c	18/5
8	H22c	18/5
9	H22d	18/5
10	H22d	18/5

lower parts of the curve pass out of the group and down to the lowest or (c) concentration. The curves which lie entirely within the limits of the Atlantic type refer to stations on the Scottish shelf, and those with extensions downwards to stations in the deepest part of the Channel.

The second or (b) concentration (on TS(11)1a) comprises curves which are entirely within it. Because of this, and in order to preserve as far as possible clarity in the diagram, they are plotted on the trans-:parency, apart from the other May curves. The stations whose curves give rise to this second concentration of points lie on the Faroe Shelf.

The last (c) concentration of depth-marks (TS(11)1) represents bottom Norwegian Sea water, occupying the deep trench of the Channel.

The distribution of the three water-types revealed by the concen-:trations (a), (b) and (c), of depth marks on the T-S diagram is shown on Figure 3. The letter A represents the Atlantic water-type, N the bottom Norwegian type, and F the Faroe Shelf type. The symbol $\overset{A}{N}$ indicates that the water column in the appropriate sub-rectangular area is compounded of the A type in the upper layers and the N in the lower.

The middle parts of four curves on TS(11)1 follow a common recti-:linear trend from the under surface of the Atlantic type to the upper surface of the bottom Norwegian Sea water. According to the principle of the T-S diagram, points on the axis formed by the above-mentioned four curves represent water due to all degrees of mixing between the two water-types at its extremities. The adjacent surfaces of these two types do not differ greatly in density, that of the under surface of the Atlantic being 27.5 and of the upper surface of the bottom rather less than 28. The straight line joining them, therefore, crosses the iso-:picnals at a small angle, indicating that stability is low, a circum-:stance which should be an aid to mixing. Other factors, of course, have also to be reckoned with, e.g. the great difference in velocity between/

between the Atlantic and the bottom water, a circumstance which probably hinders mixing.

Superimposing TS(11)1a on TS(11)1, the group of curves on the former falls about the line of mixing on the latter. The physical characteristics of F water are, therefore, such as would be produced by mixing Atlantic and bottom Norwegian Sea water. The suggestion of mixing in the region east of Faroe,formulated earlier in this paper on other grounds,is thus supported and a probable constitution of this F mixture-type put forward. While the T-S diagrams show that the Faroe water-type can be produced by a dilution of Atlantic with bottom Norwegian Sea water, the mixing is not necessarily between the representatives of these two types in the Channel, but may take place elsewhere, for example, north of Faroe.

Some individual curves require note. No. 7 on TS(11)1 is an August curve, but the reason for its appearance here will be evident later.

Curves 6 and 10 on TS(11)1a are obviously transition cases from the F to the A type.

Curve 25 stands apart from the others on TS(11)1 and 1a, further indicating that the water at this station B18b, as argued previously, is of an entirely different origin from any in the Channel proper.

Conditions in August 1911.

As previously pointed out, the hydrographic stations for August 1911 are, in the main, distributed over the southern part of the Faroe-Shetland Channel, occupying therefore a different area from that surveyed in May of the same year.

The two vertical sections constructed from the August data are VS(11)3 and/

and 4, the positions of which are given on Figure 2. It must be noted that the vertical scale of VS(11)4 is twice that of VS(11)3.

Atlantic water appears in considerable bulk on VS(11)3, where water of over 35.25 ^{0}/oo salinity occupies all depths of the two middle stations. Most of this water, in fact, exceeds 35.30 ^{0}/oo and at WW17b salinity is nowhere less than 35.34 ^{0}/oo from 50 metres to the bottom (750 metres), where the maximum salinity of 35.39 ^{0}/oo is registered. In the upper layers, temperature exceeds 13 ^{0}C., but the 10°C isotherm lies at a depth of about 75 metres and below this temperature falls off only slowly to 8 ^{0}C. at the bounding isohaline of 35.25 ^{0}/oo in the north. This mass of Atlantic water is almost entirely south of the Wyville Thomson Ridge. In the deep water north of the Ridge, and preceded by a zone of crowded isopleths indicating mixing, comes the usual fresh, cold bottom Faroe-Shetland Channel water, and in the upper 150 metres at YY19c, though temperature is high, salinity is less than 35.20 ^{0}/oo. It is clear, therefore, that the Atlantic water is not moving directly north-eastwards across the Ridge, i.e. VS(11)3 is not a longitudinal section of the Atlantic stream. It may, however, be a transverse section, in which case high salinity water should be found west of Orkney.

On VS(11)4, however, the maximum salinity registered is only 35.26 ^{0}/oo, at 70 metres and the bottom at station ZZ17a. Water of salinity exceeding 35.20 ^{0}/oo occupies most of the area between ZZ17a and ZZ17b, and as more than half of it has a temperature less than 10 ^{0}C., this body of water would appear to be of Atlantic character, though only to a modified extent. Of the two stations worked some 30 miles east of Orkney (see Figure 2), only the northern one had a salinity as high as 35.19 ^{0}/oo. There seems therefore to be no general movement eastwards of the very salt water on VS(11)3. The rapid decrease in depth towards Orkney is a factor impeding an eastward movement of any bulk of water.

Another/

Another important feature shown by the data for this area in August is the fresh water* streaming northwards from both sides of the Butt of Lewis. For the west side, this is well seen on VS(11)3, where the salinity of the upper 30 metres at the southmost station is less than 35.10^{0}/oo, and only at the bottom of this station is 35.20^{0}/oo exceeded. The influence of this fresh coastal water is also apparent in the upper 30 metres at WW17b. With the fresh water pushing northwards from WW16c are associated the highest temperatures on VS(11)3 - over 14^{0}C. and the 13^{0} isotherm runs north to just beyond XX18b.

On VS(11)4, similarly, fresh water can be seen spreading north-:wards. At the surface in the south, salinity at XX15a is less than 34.80^{0}/oo, while the freshening influence, linked with temperatures surpassing 14^{0}C., reaches to ZZ17a. At ZZ17b, though still present, it is somewhat masked, doubtless by influence from the underlying higher salinities. At A18c and B18b, however, salinity is again lowest in the upper layers.

The distribution of this coastal water can be more fully seen on the horizontal charts HC(11)6-9, where it is shown moving out from the vicinity of the Butt of Lewis and carrying its freshening influence as far north as 60^{0}N. On HC(11)7, the axis of the Atlan-:tic water lies along latitude 59^{0}30'N. as far east as 3^{0}W. The behaviour of the coastal water on contact with the body of salter water is noteworthy. On the surface, the former spreads to the north over the Atlantic water, but on HC(11)8, at 50 metres, there is a definite boundary at latitude 59^{0}15'N. between the two types of water, and no penetration of the salt by the fresh. The latter swings to the right and on reaching the easterly fringe of the Atlantic water at 4^{0}W. turns north again. Thereafter some holds on north-east towards Shetland, while the rest continues to flank the salt water and finds itself moving north-west where its influence can be traced in lower salinities and higher temperatures at YY19c, almost/

* According to Knudsen (46) most of this water originates in the Irish Sea.

almost 6° W.

The conclusion is that the lobe of Atlantic water seen in HC(11)6-9 and VS(11)3 and 4 is not a tongue of water pushing in any particular direction, but the eastern half of a cyclonic swirl, dragging round on its periphery the coastal water which had impinged on its southern flank.

The fresher water streaming northwards from the Minch is a bar to any movement of Atlantic water into the Northern North Sea by way of the Orkney-Shetland passage.

A T-S diagram, TS(11)1b, has been constructed from the August data, but the findings from it are purely negative, that is, there are no widespread water-types in the south-east of the Channel in 1911. The scattering of the August curves over the diagram, which is brought out by placing TS(11)1b on TS(11)1 and 1a is in sharp contrast to the conformity of the May curves. The inference is that the influences behind hydrographic conditions in the northern part of the Channel in May are more powerful and clearly defined than those governing conditions off the north-west Scottish coast in August.

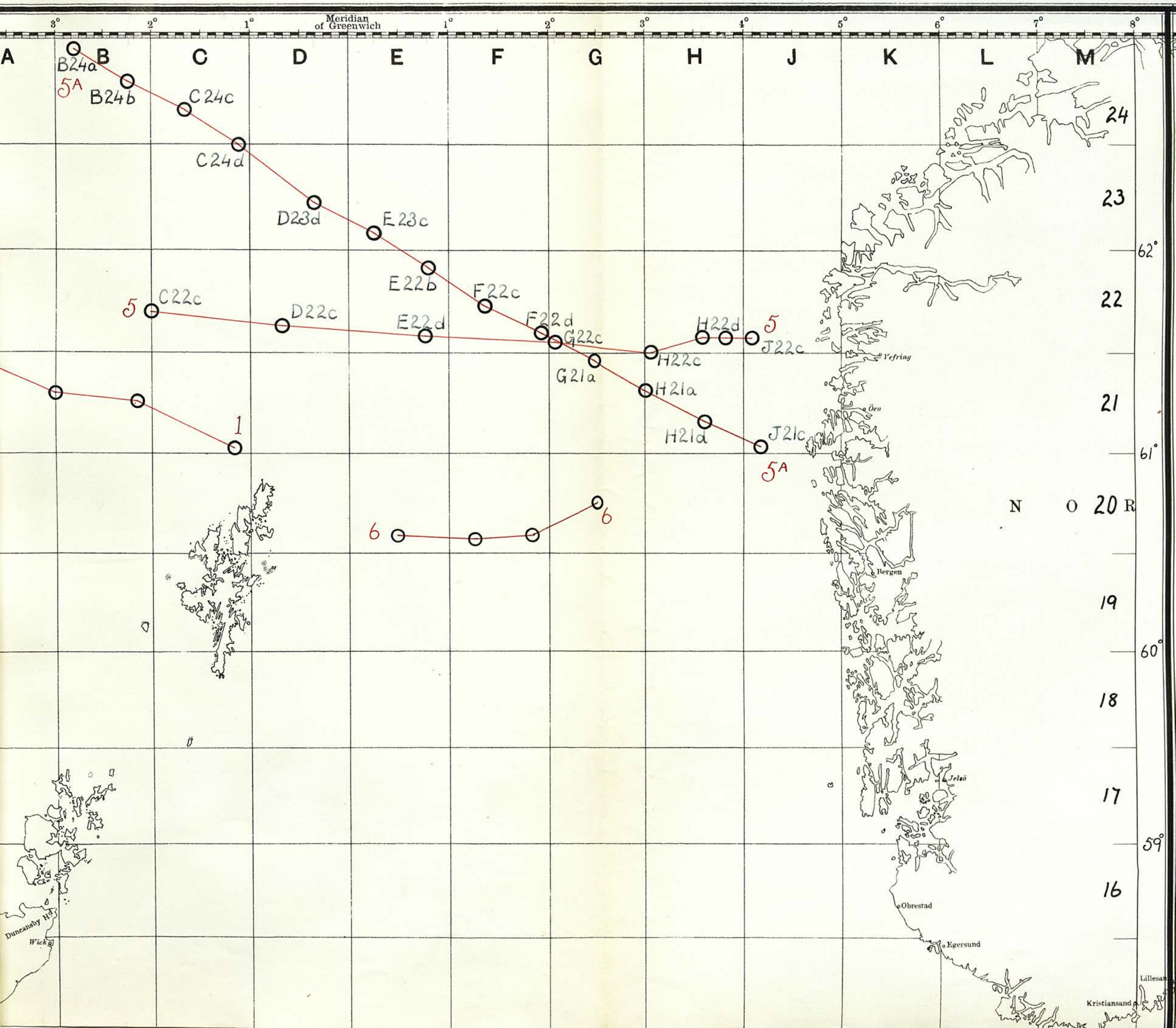
Curve No. 7 (TS(11)1) also represents a station worked in August, but it is patent that its affinities are not with the curves of TS(11)1b but with those of TS(11)1. While its later data and consequent higher surface temperatures cause its upper part to rise out of the (a) group, below a point where $\sigma_t = 27.5$ this curve conforms to type and is accordingly plotted on TS(11)1.

FIGURE 4.

FIGURE 4.

POSITIONS OF SECTIONS

SOUTHERN NORWEGIAN SEA, 1911.



SOUTHERN NORWEGIAN SEA

The progress of the Atlantic Stream in its course towards the North Sea is now to be examined in the Southern Norwegian Sea region.

The Scottish data for 1911 provide only one vertical section in the area - in May: the Norwegians, however, ran a line of stations north-westwards from Bergen at the same time. These hydrographic observations furnish an additional vertical section nd are also incor-:porated in the horizontal charts and T-S diagrams. The positions of both sections are shown on Figure 4.

Atlantic water, as defined by salinities over 35.25 ^{0}/oo occupies a large part of VS(11)5. The cross-sectional area is 61 Km^2: on the northern and southern Faroe-Shetland Channel sections it is 57 Km^2 and 60 Km^2 respectively. There thus appears to have been no diminution in volume of the Atlantic stream in passing from the Faroe-Shetland Channel to the Southern Norwegian Sea. The section in the latter region (VS(11)5), however, cannot be regarded with the same confidence as can those in the Faroe-Shetland Channel (northern part) as being a transverse section of the Atlantic stream. The following table, giving the cross-sectional areas in the previous years in which the same Southern Norwegian Sea section was worked in spring, will show to what extent the great area of Atlantic water on VS(11)5 has signif-:icance. The column headed "East of D22c" is inserted because until 1906 this station was the west end of the section. Table I has also been incorporated in order to facilitate comparison of the Southern Norwegian Sea with the Faroe-Shetland Channel.

Table.

TABLE V.

Cross-Sectional Areas of Atlantic ($>35.25^{\circ}/oo$) Water in the Southern Norwegian Sea in Spring over the Period 1903-1911.

Southern Norwegian Sea			Faroe-Shetland Channel		
Month, Year	VS (11) 5 TOTAL Km^2	VS (11) 5 EAST OF Daac Km^2	Month, Year	NORTHERN SECTION Km^2	Southern SECTION Km^2
May 1903	-	23	May 1903	27	32
June 1904	-	35	" 1904	82	63
May 1905	-	39	June 1905	81	49
April 1906	52	27	" 1906	11	44
May 1907	7	4			
			April 1908	14	29
May 1909	59	43	" 1909	68	77
			June 1909	12	45
May 1910	1	1	May 1910	4	14
" 1911	61	48	" 1911	57	60

It is at once plain that the cross-sectional area of Atlantic water in the Southern Norwegian Sea is as variable from year to year as in the Faroe-Shetland Channel.

The maximal volume of Atlantic water in the Southern Norwegian Sea in spring (assuming as before that the cross-sectional area is proportional to the volume) seems to have been present in the years 1904, 1905, 1909 and 1911 - in just those years when the Atlantic water was found to bulk larger than usual in the Faroe-Shetland Channel. The relationship of the two regions therefore appears to be a direct one as far as the total of Atlantic water is concerned.

The cross-sectional area of Atlantic water in the Southern Norwegian Sea in May 1911 is 61 Km^2 - greater than any previously recorded in spring in that area. It is also the only case where approximately equal areas of Atlantic water were found in both the Southern Norwegian Sea and the Faroe-Shetland Channel. (The two entries for 1906 are not comparable in this respect, as the month is April in the one case and June in the other.

A/

A second feature of the Atlantic water now falls to be examined, namely, the maximum salinity, together with the station and depth at which it is registered. The table below gives rhe figures for the spring months of the period 1903-1911.

TABLE VI.

Maximum Salinities on the Southern Norwegian Sea Line of Stations in Spring over the Period 1903-1911.

Month/Year	Maximum Salinity ($^{o}/oo$)	Station	Depth (m.)
May 1903	35.26	E22d	0
June 1904	.34	G22c	100
May 1905	.35	E22d	all depths
April 1906	.32	C22c	0-100
May 1907	.45	D22c	0
" 1909	.36	E22d	0
" 1910	.26	H22c	370
" 1911	.34	D22c	20

Maximum salinities in the Southern Norwegian Sea in spring are in general less than those in the Faroe-Shetland Channel (cf. Table II) a relationship which is not unexpected, since the latter region is nearer the Atlantic. In only three instances is a level of 35.34^{o}/oo surpassed, whereas in the Faroe-Shetland Channel a like number of entries (Table II) have salinities exceeding 35.40^{o}/oo. The extreme maximum, also is 35.45^{o}/oo, while in the Faroe-Shetland Channel the high value of 35.52^{o}/oo is attained. Apart from this entry of 35.45^{o}/oo for May 1907, the years in which the volume of Atlantic water was greatest were also those in which the highest maximum salinities were reached, namely, in 1904, 1905, 1909, and 1911. The maximum salinity for 1911 in the Southern Norwegian Sea is, however, equalled by one and surpassed by three other entries. In the Faroe-Shetland Channel, the maximum of 35.52^{o}/oo in 1911 was second to none.

The numb r of times maximum salinity, as shown by Table VI, occurred at each of the stations on the Southern Norwegian Sea line are/

are tabulated below.

TABLE VII.

Frequency-Distribution of Salinity Maxima in Spring 1903-11 on the Southern Norwegian Sea line of Stations in order from West to East.

Station	C22c	D22c	E22d	G22c	H22c	H22d	H22d	J22c
Frequency	1	2	3	1	1	0	0	0

Maximal salinities occur only at the five west most stations, and of these, E22d shows the greatest frequency, with the adjacent station D22c one unit behind. These two stations are on either side of the promontory of the Continental shelf which is crossed by VS(11)5. The position of the nucleus of the Atlantic water may accordingly be regarded as being in general on the Shelf and slightly to the west of station E22d.

The last column of Table VI shows little regularity in respect of the depth at which maximum salinity occurs. In 1903, 1907 and 1909, it is registered at the surface, and in 1905 and 1906, from the surface downwards, while in the three remaining entries it occurs only at a level below the surface. In the Faroe-Shetland Channel, also, maximum salinities were generally, though not always, found at the surface or in surface layers.

In 1911 (VS(11)5) water of salinity exceeding 35.30‰ lies on the spur of the Continental Shelf between D22c and E22d, the maximum salinity being attained at 20 metres at the former station. On VS(11)5a the Atlantic water is in a similar position, salinities of over 35.25‰ being centred on the narrow spur of the Shelf at F22c.

Away from the Shelf in both directions, the vertical extent of the Atlantic water diminishes. Westwards the decrease is fairly rapid, and at C22c, Atlantic water is only some 125 metres deep - considerably less/

less than at the nearest part of the northern Faroe-Shetland Channel section. Eastwards from E22d, the decrease is much slower, the 35.25^{0}/oo isohaline stretching to H22c on VS(11)5 and to H21d on VS(11)5a.

Associated with the maximum salinities on both VS(11)5 and 5a are the maximum temperatures of just over 9^{0}C. Most of the Atlantic water is over 8^{0}C. and none below 7^{0}C. In both sections, also, the lower levels of the eastern extension of the high salinity water is of lowest temperature. Some cooling influence appears to be operative in this locality. On VS(11)5a the surface of the Atlantic water is cooler than that immediately below, a chilling which is very probably the result of meeting low air temperatures.

Below the Atlantic water to the west of the Shelf on VS(11)5, cold fresh water occupies the deeps. Though salinity does not fall below 34.97^{0}/oo, negative temperatures are registered, so that this bottom water may be regarded as very closely related to the bottom Norwegian Sea type. The fact that salinities are above the usual values for this water-type and indeed attain 35.01^{0}/oo at the bottom, is doubtless connected with the presence of large volumes of Atlantic water in the Faroe-Shetland Channel and Southern Norwegian Sea at this time.

Westwards and downwards from the Atlantic water on VS(11)5a, temperature and salinity fall off rapidly and regularly to values of 34.92^{0}/oo and less and from 3^{0}C. to below zero. Here again, however, the bottom water is not all of typical bottom Norwegian Sea character, for a belt of water 300 metres broad, lying in the lower levels, has salinities under 34.90^{0}/oo. Below this, however, salinity increases slightly. In the Faroe-Shetland Channel in May 1911 the upper levels of the bottom water-type were also slightly fresher than the deepest. There/

There appears, therefore, to be a horizontal wedge, tapering south-westwards, of somewhat fresher water above the bottom Norwegian Sea type. This is of considerable thickness on VS(11)5 but of much reduced vertical extent, doubtless as a result of Atlantic influence, on the northern Faroe-Shetland Channel line of stations.

In the upper layers in the east of both VS(11)5 and 5a, very low salinities are registered. These belong to the fresh coastal water which streams northwards along the Norwegian coast and has its origin in the Baltic and south-eastern North Sea river waters. The low salinities spread westwards in a thin layer over the Atlantic water, their influence being discernable on VS(11)5 as far as G22c, and on VS(11)5a to beyond G21c, that is, to approximately 2°E. in both cases.

Temperature conditions in this fresh surface water are irregular. At the two eastmost stations of VS(11)5 an area of one or two square kilometres has a temperature less than 6°C., but westwards and downwards temperature increases, doubtless owing to warmth transmitted from the Atlantic stream. On VS(11)5a the water-column at J21c from 20 m. downwards is cooler than 6°C., but by contrast, 8°C. is exceeded at 10 m., though the surface temperature is just over 7°C. On this vertical section, also, the surface layers as far west as G21a have a temperature below 7°C - cooler than this water on VS(11)5. The chilling of the surface layer of the Atlantic water as observed on the more northerly Southern Norwegian Sea section evidently extends to the Baltic water.

Below the Atlantic and Baltic water in the eastern part of the Southern Norwegian Sea, that is, in the bottom of the Norwegian Trench, salinity and temperature again fall to somewhat low levels. This fresher, colder water, though of similar general salinity and temperature to the Baltic water, is quite distinct from the latter. On both sections VS(11)5/

VS(11)5 and 5a these two fresher types are separated by higher salinities and temperatures continuing the trend of the lobe of Atlantic water eastwards in intermediate levels to the Norwegian Continental Slope. On VS(11)5, the barrier is formed principally by a zone of slightly higher temperatures; on VS(11)5a by a zone of distinctly higher salin-:ities. On both sections, then, the deepest part of the Norwegian Trench is occupied by water whose temperature is less than 6°C. and with salinities on VS(11)5a as low as 35.08°/oo. A bottom observation is lacking on VS(11)5. This water is doubtless the source of the cooling previously observed in the lower eastern parts of the Atlantic water, but further discussion of this point is best deferred until the T-S diagrams are examined.

The horizontal charts HC(11) 1-6 show the manner in which the Atlantic water passes from the Faroe-Shetland Channel into the North Sea.

Water of salinity above 35.20°/oo spreads across the Southern Norwegian Sea to 2°-3°E. and into the north-western area of the North Sea. South of about latitude 61°N., however, at and below 50 m., this water is some 1° cooler than that of similar salinity further north. The drop in temperature is not due simply to cooling in the North Sea, for the tongue of high salinity water lying east of Shetland maintains the same temperature throughout its length, that is, the cooling was effected before entering the North Sea. VS(11)5 and 5a show that the Atlantic water is cooled on the spur of the shelf at longitude 2°E. by dilution from a cold and fresher source, and since the junction between the salt waters differing 1° in temperature extends north-east from Unst, and as all levels (except the surface) immediately to the north of this line are occupied only by warm, high salinity water, the Atlantic stream must have crossed the Southern Norwegian/

Norwegian Sea to longitude 2°E. in order to undergo the loss of 1°C. of temperature as observed on the charts. The Atlantic water thus appears not to pursue the shortest route - round Unst - in its passage from the Faroe-Shetland Channel to the North Sea, but to follow the edge of the Continental Shelf to its spur in the vicinity of 61°30'N. 2°E. and then turn south following the 100-fathom contour to the Viking Bank, where the direction is again changed and the Atlan-:tic water passes west and south-west to the east side of Shetland.

The T-S curves for the Southern Norwegian Sea in 1911 are plotted on TS(11)2 and 2a, the Scottish station-curves being on the transpar-:ency and the Norwegian on TS(11)2. These curves are separated simply in the interests of clarity, as the curves on both sheets are of essentially similar character. The grouping of the curves and of depth-marks revealing water-types is best seen on the less crowded sheet of Scottish curves, with the Norwegian curves as a supporting background.

There is a concentration of depth-marks round a salinity of 35.30°/oo and with temperatures from 8°-9°C. This represents the Atlantic water-type, and the positions at which this type occurs in the Southern Norwegian Sea are indicated by the letter A on Figure 3, thus linking this region to the Faroe-Shetland Channel. It is to be noted that the A type in the Southern Norwegian Sea is .5° cooler at the surface than in the Faroe-Shetland Channel. Curves 2 and 3 may be included in the A group also, if the high temperatures, due to the later date, August, be discounted.

The bottom Norwegian Sea type of water is represented by the cluster of depth-marks (taking TS(11)2 and 2a together) between salinities of 34.85°/oo and 34.97°/oo with temperatures from -.5°C. to approximately 1°C. As stated previously, the bottom water at

the/

the stations worked in the Southern Norwegian Sea in May 1911 is not of typical salinity and temperature. As was done in the case of the Faroe-Shetland Channel, stations where N water underlies A water are indicated on Figure 3 by the symbol $\frac{A}{N}$.

The Atlantic - bottom Norwegian Sea line of mixing is well repre:sented on TS(11)2, where a sheaf of curves runs obliquely downwards from the bottom of the A type at 8°C.

The colder fresher water at the bottom of stations H22c (VS(11)5) and H21a and H21d (VS(11)5a) may be examined in relation to the above-mentioned line of mixing, The preceding three stations are represented by curves number 8 (green) and 11 and 12 (black). The bottom of curve 8 stands apart from the others, distinguished by higher salinity than is found at depths on the remaining curves where temperature is similar. The bottoms of curves 11 and 12, however, lie along the axis of mixing. The bottom water at these stations in the Norwegian Trench is thus such as is formed by an admixture of Atlantic with bottom Norwegian Sea water. The position of the bottom of curve number 8 suggests that the observations at that depth are of abnormal character.

No further significant concentrations of depth-marks are to be found on the T-S diagrams, the Baltic water not being represented by a definite type, but simply by a series of curves stretching across the diagram to various extents. All of the Norwegian curves of this series (Nos. 10-13) have water of lower density at 10 m. than at the surface and 20 m., that is, there is density inversion in the upper:most layers. On curves 10 and 11 (green) there is inversion of temperature, but not of density. These conditions show that the fresher water in the upper layers off the Norwegian coast are turbulent, but that mixing has not proceeded sufficiently far to produce smooth and stable gradients in temperature, salinity and density.

It/

It is evident that the principal feature of the hydrography of the Southern Norwegian Sea, as of the Faroe-Shetland Channel, is the Atlantic stream. This warm salt water-type follows the edge of the Continental Shelf across the Southern Norwegian Sea and turns south with the 100 fathom contour between longs. 2-3°E., deflected to the right by the shape of the bottom and by the earth's rotation. Encount-:ering the Viking Bank, the stream is further deflected, and passes south-west to the east side of Shetland.

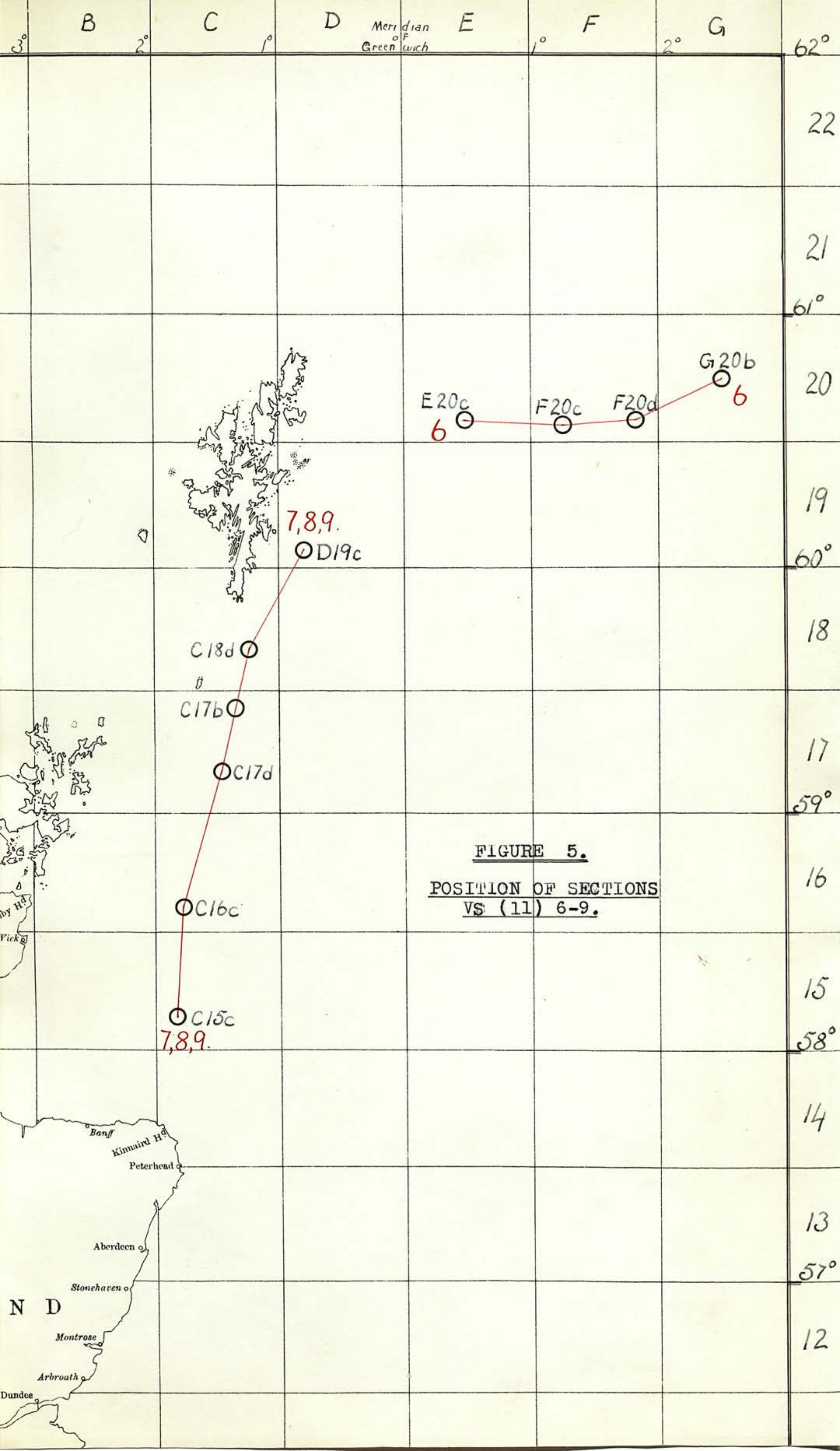


FIGURE 5.

POSITION OF SECTIONS VS (11) 6-9.

FIGURE 6.

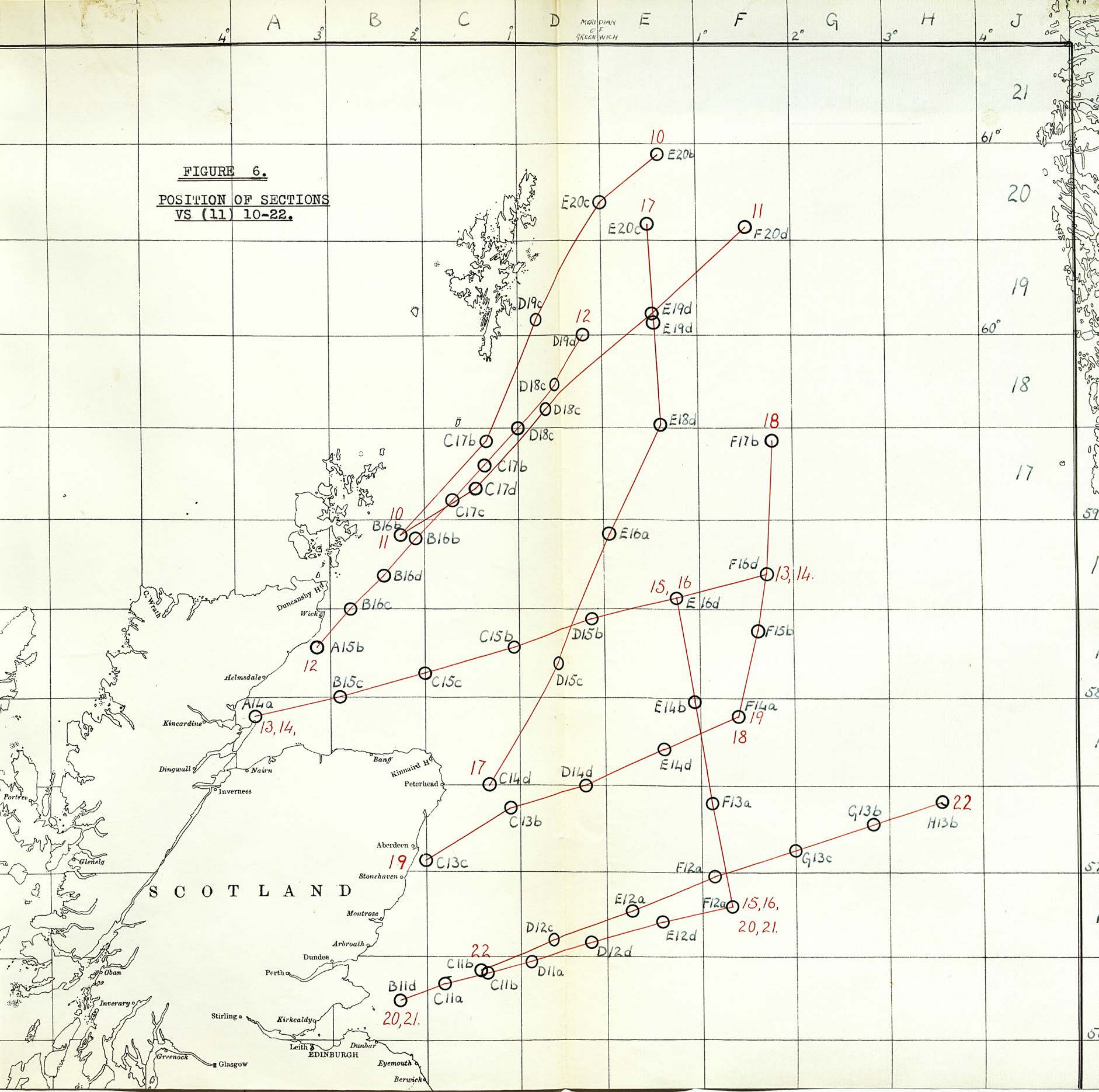


FIGURE 6.

POSITION OF SECTIONS VS (11) 10-22.

NORTHERN NORTH SEA.

The distribution of the data for the Northern North Sea in 1911 may be seen from Figures 5 and 6 which show the positions of the vertical sections for the year. As the course of the research vessel is generally straight or made up of a few rectilinear traverses, these sections comprise practically all the open-sea stations worked.

VS(11)6 may be examined first, as it is parallel to, and not far from, the Scottish Southern Norwegian Sea section, to which it is comparable also in date, being worked immediately afterwards. VS(11)6 is therefore plotted on the same sheet as VS(11)5 and so placed thereon that a given longitude on VS(11)6 is vertically below the same longitude on VS(11)5. This is done throughout with the vertical sections wherever possible, and is indicated by a line joining points with identical longitudes on two sections, or identical latitudes in the case of north-south sections.

Water of salinity exceeding 35.25^{o}/oo appears at both ends of VS(11)6, with rather fresher water between, and a tongue of less than 35.20^{o}/oo water just below the surface in the east. This freshening can be attributed to Continental water, which is known to pass north along the coast of Norway. Here its effect is seen at 2^{o}E., but salinity is not so low as at this longitude on VS(11)5. The 8^{o}C. iso-:therm, and to a much greater extent the 7^{o}C., is deeper in the salt water than in the fresher round F20c and F20d. Here is evidence that the freshening is due to admixture of cold water, and this is doubtless from bottom Norwegian Sea water.

North-/

North-Western Area.

The series of sections for the north-western area throughout the year can conveniently be examined next. VS(11)7-9 depict conditions at the same stations at different times.

April. VS(11)7 has water which may be regarded as of Atlantic derivation, that is, of salinity exceeding $35.20^{0}/oo$, only north of station C18d, and in a thin layer on the bottom just south of this. At C16c, salinity is $35.00^{0}/oo$, and thereafter it falls off more rapidly southwards. Temperature is very uniform overall at $6-7^{0}C.$ but with the maximum in the north, that is, the warmth is coming from the Atlan-:tic water and is not dependent on latitude.

May. In VS(11)8 the $35.20^{0}/oo$ isohaline has moved much further south, to C16c on the bottom, while in the north, also, salinit-:ies are higher than in April. The $35.00^{0}/oo$ isohaline almost attains C15c on the bottom, but in the upper layers the $34.90^{0}/oo$ water holds its ground, suggesting that a supply of fresh water may exist to maintain the low surface salinity here. At C17b, the lowered salinity, coupled with higher temperatures, is to be noted, for this station is opposite the Orkney-Fair Isle passages. The only comparable station west of Fair Isle is B18b, worked a week later than C17b, and recording a salin-:ity of $34.92^{0}/oo$ and temperature of $7.5-7.8^{0}$. This north-west coast water and Moray Firth water are two possible sources of the freshening influence at C17b, and as the Moray Firth area is colder than that round C17b, the north-west water, with its higher temperature, is more likely to be the source of the fresh warm water at C17b. Otherwise, temperature shows a distribution similar to that for April, except that it is $1^{0}C.$ higher overall. The fact that this rise occurs at the bottom as well as the surface shows that it is due not so much to the increase of/

of insolation with the approach of summer, which tends to warm only the surface layers, but rather to an influx of warm Atlantic water to the area.

Another north-south section VS(11)17 is available for May, and though it is some 50 miles east of the VS(11)7-9 line of stations, its date of working makes it appropriate that it be examined at this juncture.

The maximum salinity on VS(11)17 is only 35.28^{o}/oo and this in the extreme north; south of this there is a great extent of water between 35.00^{o}/oo and 35.10^{o}/oo, with at E18d a temperature below 6^{o} on the bottom. Between 10 and 20 metres, also, there is a slight steepening of the temperature gradient, but this is not marked in the north where the salter water occurs. A temperature gradient of this kind is set up by heating from above, that is, by insolation, and obviously if this effect is to have full play there must be little or no turbulence of the water. The gradient in VS(11) 17 and the uniformity of temperature and salinity in the water-masses below the slight discontinuity layer point to slow, if any, movement in the water over this area, so that it may be taken that the Atlantic influx, which is manifest on VS(11)8, does not extend to this area west of the prime meridian.

<u>July.</u> VS(11)9 shows a less regular lay-out of salinity than VS(11)8, and while salinity has risen to over 35.30^{o}/oo at C17b, and the 35.10^{o}/oo isohaline has moved south in the upper 70 m., no water of over 35.20^{o}/oo salinity occurs south of C17d, in contrast to the situation on VS(11)8. Salinities at D19c also have fallen. If a large amount of north-west water were rounding the north of Shetland and moving south along the east side of Shetland, it would force off-shore the Atlantic water which is also present there. Such a movement of fresher water would account for the low salinities in the upper layers of D19c.

On/

On passing the south end of Shetland, there would be a tendency for some of the fresh inshore water to turn west, owing to the north-flowing stream on the west side of Shetland (Drift-bottle experiments (6) show a clockwise circulation round Shetland at certain times) and this and the geostrophic force plus the effect of the slope of the bottom here would swing the Atlantic stream round to the west. If this be so, it explains the presence of the salt water at C17b, where it is to be regarded as moving west. This direction of movement is indeed indicated by the lowered surface temperature at C18d, for the passage to shallower water would tend to set up turbulence, projecting cooler water upwards from the bottom and so interrupting the course of the 10°C. isotherm on VS(11)9.

<u>August</u>. The north-western area was visited again in August: VS(11)10 and 11 are the resulting sections. They lie closer to Orkney in the south than VS(11)7-9 and have B16b in common. See Figure 6.

VS(11)10 shares station D19c with VS(11)9. Compared with July (VS(11)9) the salt water shows a further diminution from its extent in May, the 35.30 ^{0}/oo water appearing in a small body only, at D19c, while 35.20 ^{0}/oo water does not extend south of C17b. At B16b there is water of salinity less than 34.90^{0}/oo, but this cannot be compared with that of similar salinity on VS(11)9, as it is much further west than the latter. At E20c there is fresher water on the surface also, and it is significant that this station is nearest the north end of Shetland, while E20b, which is further away, has higher salinities, though the fresh influence seems to be felt even here, for the salinity at 10 m. is less than that above and below it. Fresher water thus lies some distance off Shetland, but the hypothesis advanced in connection with VS(11)9 explains this circumstance and also the presence of the isolated body of water of salinity exceeding 35.30^{0}/oo at D19c. The Atlantic inflow to the North Sea appears to be "shooting-off" the north end/

end of Shetland, while the fresher, north-west coast mixture on its right-hand side seems to flank the Isles more closely and moves more or less along the section in the upper layers between D19c and E20c. The Atlantic water, on the other hand, appears to be cut more trans-:versely by the section, which supports the hypothesis that it is recurving back on Shetland after having passed east from the north of Unst.

On VS(11)10 there is a steady fall in temperature from above 13°C. on the surface to below 9°C. on the bottom. At the south end, however, the bottom temperature is 11°C., that is, the warming-up is being transmitted downwards. The depth of water is less here, and tides strong, leading to mixing, which doubtless explains this high bottom temperature.

As on VS(11)10, there is on VS(11)11 an isolated body of over 35.30^{0}/oo water at the bottom, in this case at D18c. The fact that this high salinity water is farther south on VS(11)11, which is more offshore, than on VS(11)10, further supports the contention that this Atlantic water is recurving back on Shetland.

Temperature conditions differ from those obtaining on VS(11)10, for the surface is 1°C. warmer and the bottom 1°C. cooler than on the latter section, while the isotherms north of D18c are crowded together between the depths of 20 and 50 m. This is a well-developed temperature gradient, forming a horizontal discontinuity layer at the depth to which solar warming is effective. South of D18c this layer is non-existent and the surface becomes cooler and the bottom warmer, greater mixing, related to tidal action, being again the probable explanation. The presence of the steep temperature gradient between depths of 20 and 50 metres on VS(11)11, and a much less marked development of this condition in VS(11)10 points to slower movement of the water on VS(11)11 than on VS(11)10. Relative quiescence allows the play of insolation full scope in the former to produce its surface heating effect,/

effect, whereas in the latter, turbulence is tending to equalise temperatures throughout the water-mass. The establishment of this temperature gradient demonstrates that the Atlantic influx, which the sections show to have reached a maximum in May, has been spent, and the warm salt water which had entered the Northern North Sea is lying more or less quiescent in August, except in the extreme west, where there is still apparently a stirring of the water-mass.

<u>October</u>. The last section, VS(11)12, in the north-western area is for October and is similar in position to VS(11)11.

Salinity has decreased from the August level by .10 $^{0}/_{00}$ overall, and in place of a block of salt water at D18c as in VS(11)11, there is water fresher than its surroundings. Since this position is full in the track taken by water from round the north of Shetland, it appears either that though Atlantic water is no longer entering the North Sea in quantity, the north-west Scottish coast water is still penetrating at least as far south as D18c, or that the fresher water in the centre of the Northern North Sea is spreading west in the absence of resistance from Atlantic water.

The tendency of the isohalines to the vertical, and the uniformity of temperature on the section are due to the play of the convection currents which flourish at this season. Owing mainly to its greater capacity for heat, the sea does not attain its maximum or minimum temperature till after that of the air above it, that is, the warming and cooling of the sea lags behind that of the air. The result is that by October the air is much colder than the sea and the surface layers are therefore chilled. Cooling increases density, with the result that the surface layers sink, carrying with them a temperature which, though less than it was initially, still exceeds that of the layers to which its augmented density now brings it. In this way, warmth/

warmth is transmitted to the air and temperature differences in the sea smoothed out, while at the same time irregularities of salinity tend to disappear as a result of the mixing process. The consequence of the effect of convection currents on bottom temperatures is that the maximum temperature is not reached till late in the year. The figures for the rectangular area C17 are:-

April	May	July	August	October
6-7°C.	7-8°C.	9-10°C.	8-9°C.	10-11°C.

The maximum temperature occurs in October.

Convection currents do not appear to have full scope at the north end of VS(11)12, for salinity is somewhat irregular and temperatures lower. Some slight degree of circulation seems to persist here.

South-West and Centre of Northern North Sea.

Sections VS(11)13-19 cover the remainder of the area of the Northern North Sea over which hydrographic cruises were made in 1911. The sections are in two main classes, one running eastwards from the Moray Firth, the other north-south almost in the centre of the area.

February. VS(11)13 extends eastwards from the Dornoch Firth almost to longitude 2°E. The vertical isohalines and uniformity of temperature show that the effect of the winter's convectional cooling is still predominant. East of C15b the water is particularly featureless and this fact is to be noted in connection with VS(11)17, where, in May, the west-centre of the Northern North Sea was of the same salinity - just over 35.00°/oo, and very uniform at this figure.

May. Three months later the identical line, VS(11)14, while still of the same degree of salinity, is more complex. In the Moray Firth region, salinity increases from the surface downwards, and this freshening of the surface extends out east over the 35.00°/oo water. While some of the bottom water in the east is cooler than 6°C. (compare/

(compare VS(11)17) the rest of the water shows a rise of temperature since February, particularly the inner Moray Firth, where the high surface temperature (for May) of $10^{o}C.$ is doubtless due to the influence of the surrounding land, which warms up in response to the northing sun more rapidly than the sea.

Centre of North Sea.

VS(11)15 is north-south in the centre of the North Sea in February and is very featureless, but the presence of $35.00^{o}/oo$ water in the north in relation to that of the same salinity on VS(11)13 and 17 is to be noted. In May, however, salinity on the same line, VS(11)16, has fallen off somewhat, in contrast to what happened in the north-west area, for there salinity reached a maximum in May. At E14b there is on the surface a small body of warm and fresh water which may be either Scottish or Continental coast water.

August. VS(11)18 and 19 are lines of stations in the centre of the Northern North Sea in August, and are plotted on the same sheet as VS(11)17 on account of similarity of position. VS(11)18 has at F17b water of over $35.20^{o}/oo$ salinity from 40 m. downwards. Above this is fresh Baltic water, and round the junction between these two waters of different density a discontinuity layer exists. The saltest bottom water has a higher temperature than that further south, though the depth here is less. South of F16d, too, the surface temperature is slightly higher, and the temperature gradient steeper. Reference to VS(11)19 shows that these conditions fade out just west of F14a. The water between F14a and F16d thus seems to be in a relatively stagnant condition, while the salter water at F17b doubtless owes its higher bottom temperature to slow replacement from the warm Atlantic source.

VS(11)19 is occupied for the greater part by $34.90^{o}/oo$ water, west/

west of which the salinity falls off rapidly towards the Scottish coast. As far as D14d, coastal water can be seen spreading out over the surface, while surface temperature falls and bottom temperature rises westwards. Mixing by tidal movement is probably the explanation.

The horizontal charts HC(11)1-4 illustrate conditions over the western area of the Northern North Sea in May 1911 and link up this region with the Southern Norwegian Sea.

The saltest water, which is to be regarded as of Atlantic origin, is confined to the extreme west, and reaches farther south in the lower layers than in the upper. At the bottom, the 35.20°/oo isohaline passes a little south of the 59th parallel. East of the prime meridian the isohalines curve sharply northwards at and above 50 m., marking the junction with the central inert mass of fresher water seen on the sections in the centre of the area. The fact that the junction is more defined in the upper half of the water-column suggests that the movement of the Atlantic water is greater in these levels than at depths exceeding 50 m.

At the surface the central area is warmer than the western, but at 50 and 100 m. the gradient is in the opposite direction.

The charts for August, HC(11)6-9, cover a greater area and afford a fuller picture of the western part of the Northern North Sea than do the charts for May. It must be borne in mind, however, that data are absent from the rectangular area bounded by lats. 58°N. and 59°N. and longs. 1°E and 1°W. As an approximation to the truth, the isopleths have been interpolated in this area on the same basis as for the rest of the charts.

These August charts record a change in hydrographic conditions since May./

May. The axis of high salinity water is on the whole not so strictly confined to the west as in May, and the lobe of over 35.30^{o}/oo water does not reach so far south, but on the other hand has a greater breadth than formerly. Since May, surface temperatures have risen some 6^{o}C. and bottom only 2^{o}C. The greater rise on the surface is the outcome of the interval of time between the two sets of charts.

On HC(11) 6 the axis of the Atlantic water as defined by salin-:ities exceeding 35.20^{o}/oo stretches from north of the Viking Bank to off the south-east of Shetland, and a tongue of higher salinities extends from this southwards to lat. 59^{o}N. and then swings to the south-east. Much fresher water appears around and in the rectangular area F18, and these lower salinities are doubtless to be attributed to the presence of Baltic or Continental water which has spread west from the Norwegian coast. Salinities are low, also, off the Buchan coast, the reason here being dilution from fresh Scottish coastal water. Temperature is highest, over 15^{o}C., in the east, and decreases by 1^{o} to 2^{o}C. westwards.

At 20 m., HC(11)7, the 35.20^{o}/oo isohaline is in a similar position to that which it occupies at the surface, but the isohalines of 35.10^{o}/oo, 35.00^{o}/oo and 34.90^{o}/oo have pushed further south-east along the axis of highest salinity. The very fresh water in the centre of the area does not now appear, being confined to the layers above 20 m. Temperature is at a maximum of over 14^{o}C. in the centre of the Northern North Sea and in an area stretching from the centre towards Shetland, while north and west of this, temperature decreases. The presence of less than 12^{o}C. water off Orkney, together with the fact that the nearest water of a similar temperature is west of these islands, suggests some movement of water into the North Sea by the Orkney-Fair Isle passage.

With increase of depth to 50 m., HC(11)8, conditions alter con-

:siderably/

considerably. Water of salinity over 35.30°/oo appears on the south-east side of Shetland, while the 35.20°/oo isohaline reaches south almost to 59°N. It also pushes south in the centre of the North Sea and west and north round the south of Shetland. The 35.10°/oo, 35.00°/oo and 34.90°/oo isohalines are also farther south than at 20 m. and 50 m. in May. Moreover, the axis of highest salinities has moved slightly further west, being now nearly coincident with the meridian of 1°W. as far south as lat. 58°N. where it again swings south-eastwards.

The gradient of temperature is now in the opposite direction to that found in the upper 20 m. The minimum of less than 7°C. is in the centre of the area and projects north-westwards towards Shetland under the lobe of warmer water at 20 m. The increase west-:wards of temperature is rapid, to 10-11°C. on the axis of saltest water, the difference of 3°-4°C. from temperatures in the central area being greater than that between the same areas at 0, 20 and 100 m.

At 100 m., HC(11)9, the lay-out of the isohalines is similar to that found in May, that is, the axis of salt water is strictly confined to the north-west. Unlike May, however, the 35.30°/oo iso-:haline reaches south to lat. 59°30'N. and while the 35.20°/oo isohaline is similarly situated in both months, the 35.10°/oo isopleth lies further south-east than it did in May. East of long. 1°E. on HC(11)8, the 35.20°/oo and 35.10°/oo isohalines bend south, with a tongue of fresher water separating this central salter water from that in the west. This lobe was already developing at 50 m., where, as at 100 m., it is, in addition, the axis of lowest temperatures, while at 20 m. it was the axis of highest temperatures. The great range of temperature, namely 8°C., as between surface and bottom, points to relative stagnation in this water, and its lower salinities show that it is unaffected by the Atlantic inflow. It forms, therefore, a/

a great lobe of more or less immobile water with a sloping front, such that it is some 60 miles off Shetland at 100 m. and occupies higher and higher layers south-eastwards, till it floods all depths in the centre of the Northern North Sea. The result of the pres-:ence of this barrier is the progressively greater confinement, with increasing depth, of the Atlantic influx to the north-west. Once the end of this lobe is passed, the salt water seems to be able to spread out to the south-east.

It has been found convenient and useful to plot the T-S curves for the Northern North Sea in 1911 on three diagrams, the first embracing the months February-April, the second May-July and the third August-October. The T-S diagrams, therefore, in addition to their usual functions, enable the hydrographic conditions of the North Sea in 1911 to be summarised over quarterly periods.

<u>February-April</u>. On TS(11)3 the curves fall into two groups, a salter and a fresher, both of which have a very low range of temper-:ature. The salter of the two groups can be sub-divided on a basis of salinity. The diagram thus enables the station-curves and therefore the waters of the Northern North Sea at this time to be classed in three groups:- type A with salinity 35.15°/oo - 35.35‰ and temperature 6.5°C; type B with salinity 35.00°/oo - 35.10°/oo and temperature 6.4°C; and type D with salinity 34.60°/oo -34.80°/oo and temperature 6°C. The facts that these types do not overlap on the diagram and that similar hydrographic conditions were found through-:out the period in those sub-rectangles which were visited more than once, are the justification for plotting the data for February and April on one diagram.

The sub-rectangular areas in which the above types of water occur in the Northern North Sea are indicated on Figure 7 by inserting in them/

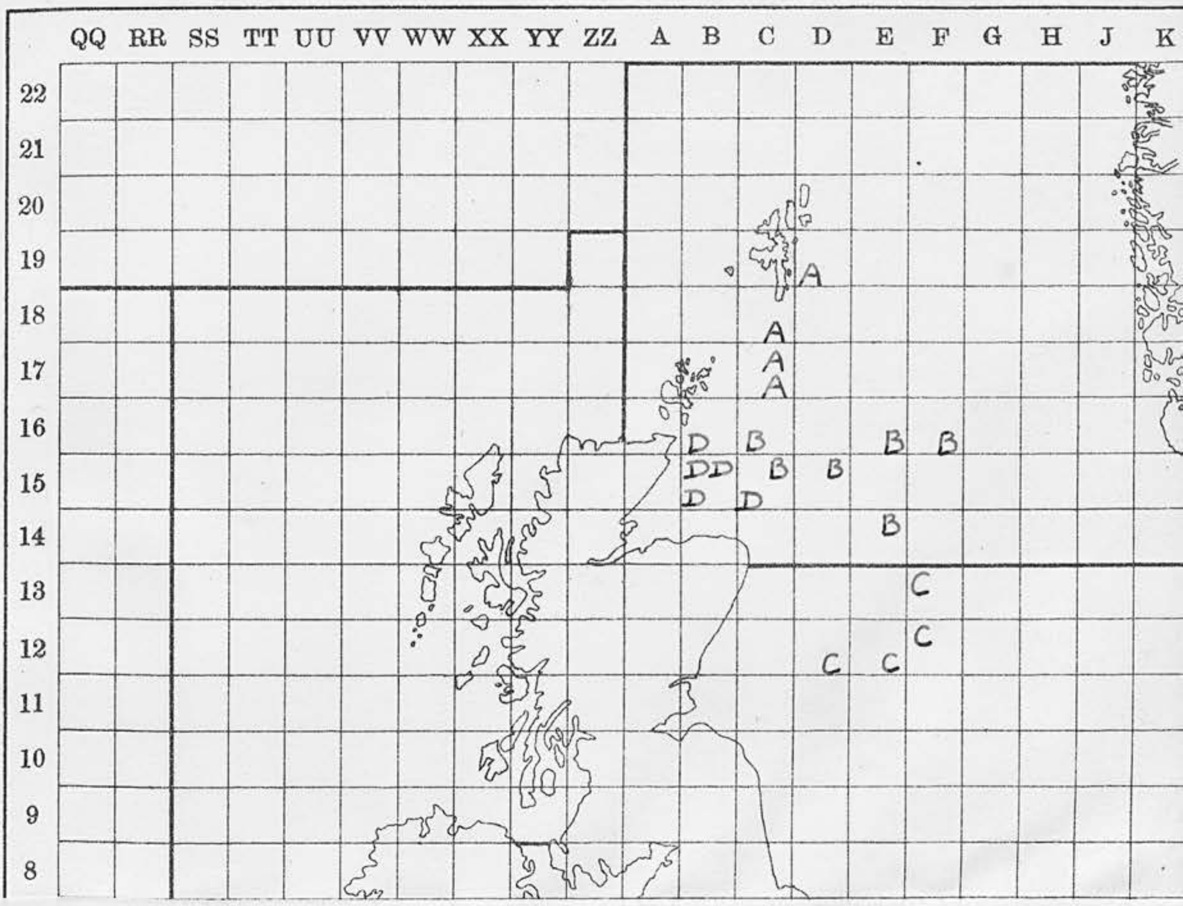


Figure 7.

Distribution of Water-Types, February and April 1911.

Salinity and temperature of the water-types shown on Figure 7, together with the positions and dates of the stations whose T-S curves make up the grouping which represents the above types.

TS(11)3

A

($35.15-.35^{0}/oo \times 6.5^{0}C$)

6	C18d	11/4
7	C17b	11/4
8	C17d	11/4
14	D19c	13/4

B

($35.00-.10^{0}/oo \times 6.4^{0}C$)

9	C16c	9/4
10	C15b	12/2
15	D15b	12/2
16	E16d	12/2
17	E14b	12/2
18	F16d	12/2

D

($34.60-.80^{0}/oo \times 6^{0}C$)

1	B16c	9/4
2	B15a	9/4
3	B15b	8/4
4	B15c	13/2
5	B15c	17/4
11	C15c	13/2
12	C15c	8/4
13	C15c	18/4

C

($34.85 - 35.00 \times 6-6.75^{0}C$)

TS(11)6

15	D12d	11/2
20	E12d	11/2
22	F13a	11/2
24	F12a	11/2

them the appropriate letter. A regional division of the area covered is at once apparent. The north-west is saltest, the Moray Firth freshest, and the centre intermediate in salinity, but nearer to the A than to the D type. The A type, on account of its higher salinity, is to be regarded as the representative in the North Sea of the Atlanti stream. The freshness of the D type can be accounted for by the pres-;ence of Scottish coast water, while B is the central complex which will be seen later to persist in its occupation of that area.

May, June, July. The diagram for this period, TS(11)4, is more complicated than TS(11)3, but close inspection reveals that the curves on it are equally capable of being resolved into groups. The manner of naming these groups is based on that used for TS(11)3, that is, where a group has remained unchanged through the months or modified by season or Atlantic influx in such a way that slight doubt can exist as to its relationship with the earlier type, then the same type-letter is applied in both cases. For example A is in both the water most nearly related to the pure Atlantic type as found in the Faroe-Shetland Channel and Southern Norwegian Sea. This system of nomenclature is adhered to throughout as far as possible.

On TS(11)4, then, there is a concentration of depth-marks with a salinity of $35.20^{\circ}/oo$ to $35.30^{\circ}/oo$ and temperature of $6.5\text{-}7.5^{\circ}C$. This is the saltest water on the diagram, and as the observations for this type of curve were made in the north-west of the area, it is clear that Atlantic water is involved, and this type is accordingly named "A'". Stations whose curves lie wholly within the imits of the A con-:centration are styled A^{x}. These two types are plotted on Figure 3. A series of curves lies vertically above type A' on TS(11)4, that is, they are of similar salinity, but warmer, $8^{\circ}C$. on the bottom and upwards of 11° on the surface. These are for stations worked in July, and are plotted as A on Figure 8. Reference to TS(11)2 at this juncture will reveal the composition of the A type of water in the

Northern/

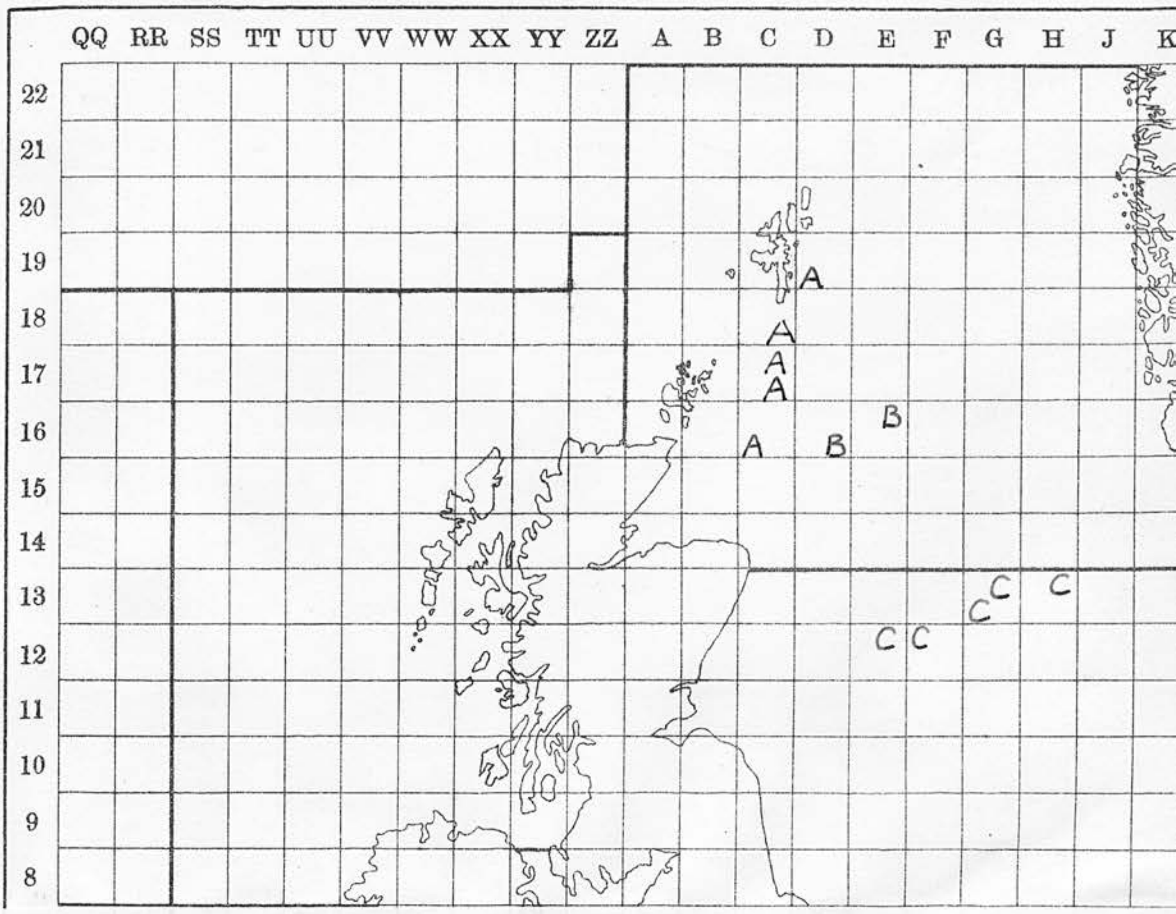


Figure 8.

Distribution of Water-Types. July 1911.

Salinity and temperature of the water-types shown on Figure 8, together with the positions and dates of the stations whose curves make up the groupingswhich represents the above types.

A

$(35.20-.30^{0}/oo \times 8^{0}C)$

TS(11)4

3	C18d	6/7
5	C17b	6/7
7	C17d	6/7
9	C16c	6/7
16	D19c	7/7

C

$(34.85-35.00^{0}/oo \times 6-6.75^{0}C$

TS(11)6

19	E12b	14/7
26	F12a	14/7
27	G13b	14/7
28	G13c	14/7
29	H13b	15/7

B

$(35.00-.10^{0}/oo \times 5.75-6.5^{0}C)$

TS(11)4

17	D16d	19/7
25	E16b	20/7

Northern North Sea and at the same time establish a connection between this region and the Southern Norwegian Sea. The co-ordinates of the A′ water, 35.25 $^{0}/_{00}$ x 7 ^{0}C., give a point which falls on the line of mixing between the undiluted Atlantic water and the bottom Norwegian Sea type. The A′ type in the Northern North Sea in May is thus a product of the dilution of Atlantic water with Southern Norwegian Sea bottom water.

To complete the water-type chart for May, the station curves on TS(11)2 which are of the A′ type in their middle parts, but with fresh Baltic water on top and colder Norwegian Sea water below are plotted on Figure 3 as A^{0}.

Returning to TS(11)4, another cluster of depth-marks can be found, with limits of salinity 35.00 $^{0}/_{00}$ - 35.10 $^{0}/_{00}$ and of temperature 5.75-6.5 ^{0}C. When the curves worked in May in this group are plotted on Figure 3 as B, this type forms a body of water in the centre of the Northern North Sea distinct from A but with two stations B^{x} in the south which indicate a transition to fresher water. Two of the stations in the B group were worked in July: their positions are shown on Figure 8. The sole difference between B water in May and in July is the higher surface temperature in the latter month. This B water, then, retained its character from May to July, except for a rise in surface temperature due to advance of season.

Curves 1, 11, 12 and 14 make it possible to draw a line bounding A on the south in May (Figure 3) from fresher water in the Moray Firth, and the two B^{x} allow this line to be continued southwards to delimit B on the south. There is thus a regional division south-eastwards from Orkney separating water-types as in February-April.

The B type is mainly a bottom type, the surfaces of the curves rising out of it to greater heights with progressively later date. This cold bottom water, however, persists from May to July and is indeed identical/

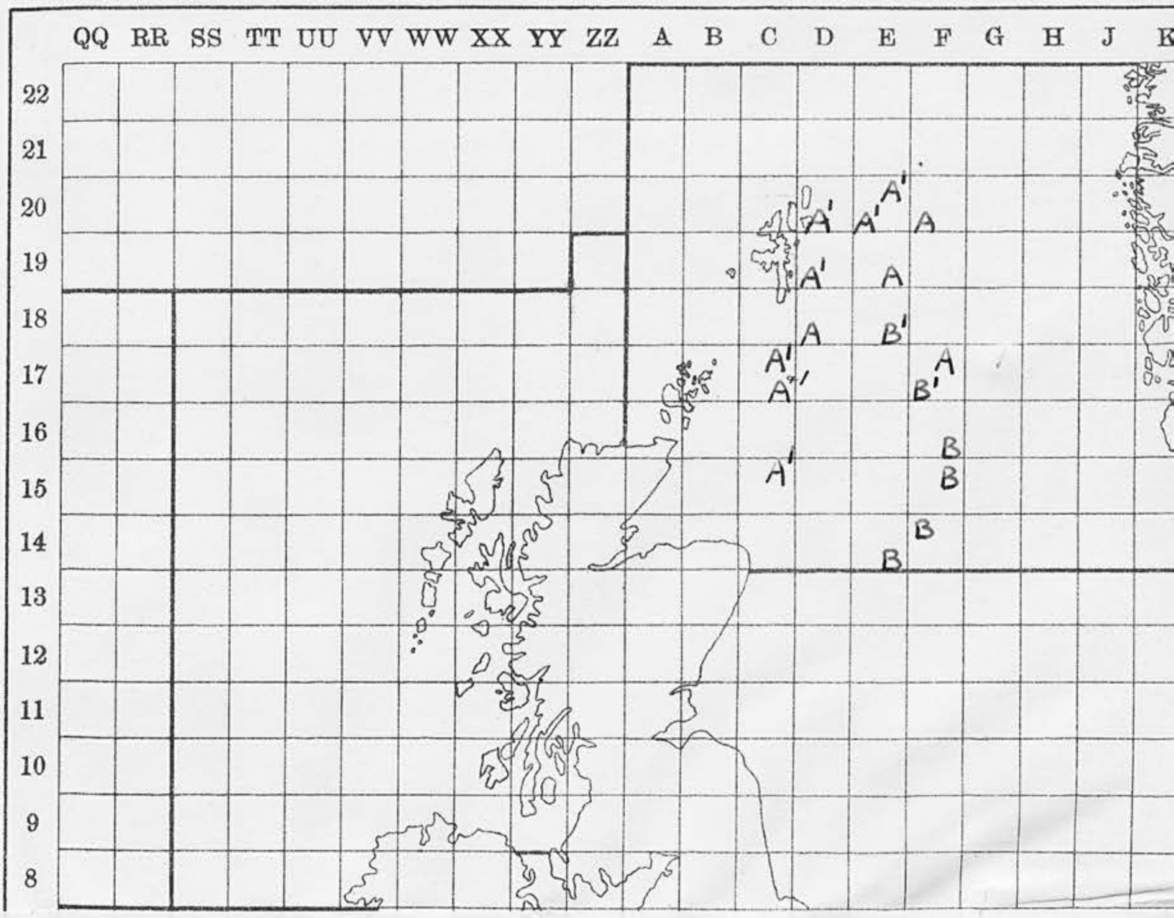


Figure 9.

Distribution of Water-Types, August 1911.

Salinity and temperature of the water-types shown on Figure 9. together with the positions and dates of the stations whose curves make up the grouping which represents the above types.

TS(11)5

A.

Bottom 35.15-.35°/oo x 7°C.
Surface 35.20°/oo x 14°C.

9	C17d	16/8
15	D18c	16/8
21	E19d	10/8
24	F20c	10/8
25	F17b	9/8

A'

Bottom 35.15-.30°/oo x 9°C.
Surface 35.20°/oo x 14°C.

5	C17b	17/8
8	C17d	16/8
11	C15b	29/8
12	D20c	11/8
13	D19c	16/8
19	E20b	10/8
20	E20c	12/8

B

Bottom 34.90-35.00°/oo x 6.5°C.
Surface34.90°/oo x 15.5°C.

23	E14d	8/8
27	F16d	8/8
28	F15b	8/8
29	F14a	8/8

B'

Bottom 35.10°/oo x 6.5°C.
Surface 35.05°/oo x 14-15°C.

22	E18d	9/8
26	F17c	9/8

identical with that found in the same area in February and April. This fact affords further grounds for regarding this B type in the centre of the Northern North Sea as lying more or less stagnant.

<u>August</u>. On TS(11)5 there are two groups of curves, both with high salinity, but with a difference of almost $2^{\circ}C.$ in their bottom temperatures. The first is type A, with salinity $35.15^{\circ}/oo$ - $35.35^{\circ}/o$ and temperature $7^{\circ}C.$ at the bottom and with a surface salinity and temperature of $35.20^{\circ}/oo$ and $14^{\circ}C.$ The second, A', is characterised by salinity of $35.15^{\circ}/oo$ - $35.30^{\circ}/oo$ and temperature of $9^{\circ}C.$ on the bottom and similar surface conditions to those for A. When plotted on Figure 9 the A and A' water occupies the north-west of the Northern North Sea, with the A water on the east and A' to the west. Both types are clearly of Atlantic origin, but are equally clearly distinct on TS(11)5. "A" resembles closely (in all but surface temperatures, the rise in which is accounted for by advance of season) the A' type in May. There was a July A type with a bottom temperature of $8^{\circ}C.$ and now there is A' in August with a bottom temperature of $9^{\circ}C.$, but <u>at the same time</u> there is A with bottom at only $7^{\circ}C.$ It seems as if a new pulse of Atlantic water entered the North Sea but did not entirely displace the earlier influx, which is seen as A in August. The higher bottom temperature of A' as compared with A in August, is not due to turbulence alone, though A' is, certainly, more coastal than A, for there is a difference of only $.5^{\circ}$-$1^{\circ}C.$ in surface temperature between A and A' whereas there are $2^{\circ}C.$ between their bottoms. Data do not exist to enable us to find whether A' in August ($9^{\circ}C.$ bottom) and A in July (8° bottom) are separate pulses or whether the rise in temperature is not due to the time-interval of one month.

Two other sets of curves lie to the left of A on TS(11)5, with bottom temperatures of $6.5^{\circ}C.$ but with a difference of $.10^{\circ}/oo$ in salinity/

salinity. Though this is a small difference, the two groups are distinct from each other and the surface temperatures of the salter are .5° C. lower than those of the fresher. They are, however, close enough to be styled B and B′ respectively, and Figure 9 suggests that the modification of B to B′ is brought about by the position of the latter water-type, which has A water on three sides of it and is, no doubt, subject to a certain amount of mixing.

October. On TS(11)5 the October curves separate themselves into two very distinct groups, one with salinity of 35.15°/oo to 35.25°/oo and temperature 10.5° - 11° C. This is undoubtedly the relic of the A′ type in August, in which the temperature range from surface to bottom has been largely smoothed out by the convection currents which are active in the latter part of the year. The mean temperature, 10.75°C., of this water-type in October is .5°C. less than the arithmetic mean of surface and bottom in August, and when it is remembered that (1) some heat must be given off to the atmosphere in the intervening weeks between August and October and (2) that temperature in August falls off more rapidly downwards than it increases upwards from the bottom, thus making the arithmetic mean rather higher than the average temperature of the water-column, it will be seen that the correspondence in temperature is so close that this water-type in October can be regarded as a derivative of A′ in August, the alteration in vertical temperature distribution being the result of convection currents. The October type occurs at C17b, D18c and D19d.

The other October group on TS(11)5 is warmer and fresher and bears no discernible relationship to any type previously observed in the Northern North Sea. October conditions are, indeed, seen as well on VS(11)12 as on the T-S diagram.

MIDDLE NORTH SEA.

Hydrographic observations in the Middle North Sea afford three vertical sections eastwards from the Firth of Forth, as shown on Figure 6, but some stations were also worked off the mid-east Scottish coast, and the data for these are included in T-S diagram TS(11)6.

February. VS(11)20 again illustrates the effect of convection in vertical isohalines and lack of variation in temperature, the area west of D11a being just under, and east of this station just above, 6°C. The warmer salter water at the bottom of B11b is probably derived from the body of water of similar characteristics some 50 miles further out to sea. The section, however, gives a transverse cut of this water, so that the stream supplying it must be of a meridional rather than simply east to west course.

May. By May, VS(11)21, salinity has risen, especially in the middle part of the section. A steepened temperature gradient has also been established at 20-30 m. depth and the tendency of the isohalines to make a bend at this depth suggests that this is a definite discontinuity layer.

July. VS(11)22 shows similar salinities to those in May over the area it has in common with VS(11)21, except that fresh water appears on the surface at the west end — Scottish coastal water. At the east end of the body of 34.90°/oo water which occupies a large area between E12b and H13b, Baltic fresh water appears on the surface, and here the well-defined temperature gradient which lies at 20-30 m. further west is deeper by 10 metres. Although

a/

a greater depth has been warmed up here in the east, temperatures in the upper layers are highest in the west at C11b, where the bottom temperature, also, is 3°C. higher and the gradient steady from the surface down to 30 m.

T-S curves for all the open-sea stations worked in the Middle North Sea in 1911 are plotted on TS(11)6.

There is one definite concentration of depth-marks at $34.85^{\circ}/oo$ - $35.00^{\circ}/oo$ and 6°-6.75°C. This is named the C type. The type includes stations in February, May and July. In February the curves are wholly within the group, in the two later months the upper ends of the curves rise out of it, in May to surface temperatures of 9-10°C. and in July to 14°C.

The remainder of the curves on TS(11)6 are of varying salinity and temperature, but all fresher than the C type. Stations giving this heterogeneous set of curves are with one exception situated west of longitude 1°W.

The February stations having C type water are plotted on Figure 7 where they occupy the central area, making a second east-west boundary by limiting the B water on the south at about $57^{\circ}30'$N. or the 50 fathom contour.

Those stations with this type of water in their bottom layers in May and July are also indicated by the letter C on the appropriate charts, Figures 3 and 8, where this type again occurs in the centre of the Middle North Sea.

The persistence of this somewhat fresh and cold C type of bottom water from February to July is analogous to that of B water in the centre of the Northern North Sea. It would seem to indicate that the/

the Atlantic influx to the North Sea in May did not affect this area, unless the very slight increase in salinity of the C water in July may be attributed to that source.

Summary of Hydrographic Conditions in the North Sea in 1911.

Salt water closely allied to the Atlantic type found in the Faroe-Shetland Channel and Southern Norwegian Sea was found at all seasons on the north-west side of the Northern North Sea. In the spring months, this type with salinity 35.15°/oo - 35.35°/oo and temperature 6.5° C. lay just south of Shetland. In May, the volume of invading Atlantic water increased and spread further south, to latitude 59° N., while salinity and temperature rose to 35.20-.30°/oo and 7°C. In August, the volume of Atlantic inflow was further augmented, salinity being similar to that in May. The extension southwards, however, was not so great, but the tongue of salt water was broader than in May. A second inset seemed to take place in August, wedging the earlier influx eastwards off Shetland. In October, the salt warm water diminished considerably in extent and formed quite a small lobe south of Shetland.

In the centre of the Northern North Sea the water-masses lay relatively motionless throughout the year. Salinities were lower (35.00°/oo - 35.10°/oo) than in the western area and bottom temperatures did not rise with advance of season, remaining at the low figure of 6.5°C. Surface temperatures, on the other hand, rose to greater heights than in the Atlantic water, and fresh Baltic water spread westwards also in the surface layers. The central bottom type lay/

lay north of the 50 fathom contour and 57°30'N., south of which was a similarly cold bottom type which persisted from February to August with even higher surface temperatures (maximum 15.5°C.) in the height of summer than in the Northern North Sea, but with lower salinities - 34.85°/oo - 35.00°/oo. The temperature of both of these bottom types seemed to be determined by, and to remain at, the minimum reached after cooling through the previous winter, temperatures in the upper layers only being affected by the onset of summer.

The waters adjacent to the Scottish coast were fresher than those offshore.

THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS

DURING THE YEAR 1912.

THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS DURING THE YEAR 1912.

FAROE-SHETLAND CHANNEL.

The Faroe-Shetland Channel area was visited only once in 1912, between the 30th of May and the 2nd of June, when the usual two lines of stations, with the exception of C21c, were worked. This station, however, was visited on the 21st of May, and the series of observations then obtained have been incorporated in VS(12)1. The southern section, VS(12)2, has been extended into the Northern North Sea by the inclusion of the contemporaneous station C18d. Figure 10 gives the positions of the two sections.

S a l i n i t y.

There appears to be considerably less Atlantic water in the northern part of the Faroe-Shetland Channel in 1912 than in 1911. The following are the cross-sectional areas in these two years:-

Month, Year	Northern Section	Southern Section
May 1911 May/June 1912	57Km^2 21Km^2	60 Km^2 24 Km^2

The areas in 1912 are little more than one-third of those in 1911. In the spring months of the period 1903-11, as shown on Table I, the area on the northern section in 1912 was exceeded by five of the nine entries, and on the southern section by eight of the nine. In respect of the volume of Atlantic water present, 1912 may therefore be regarded as a lean year. The relationship of its two sections, however, is similar to that generally found - the area of Atlantic water on the southern section exceeds that on the northern.

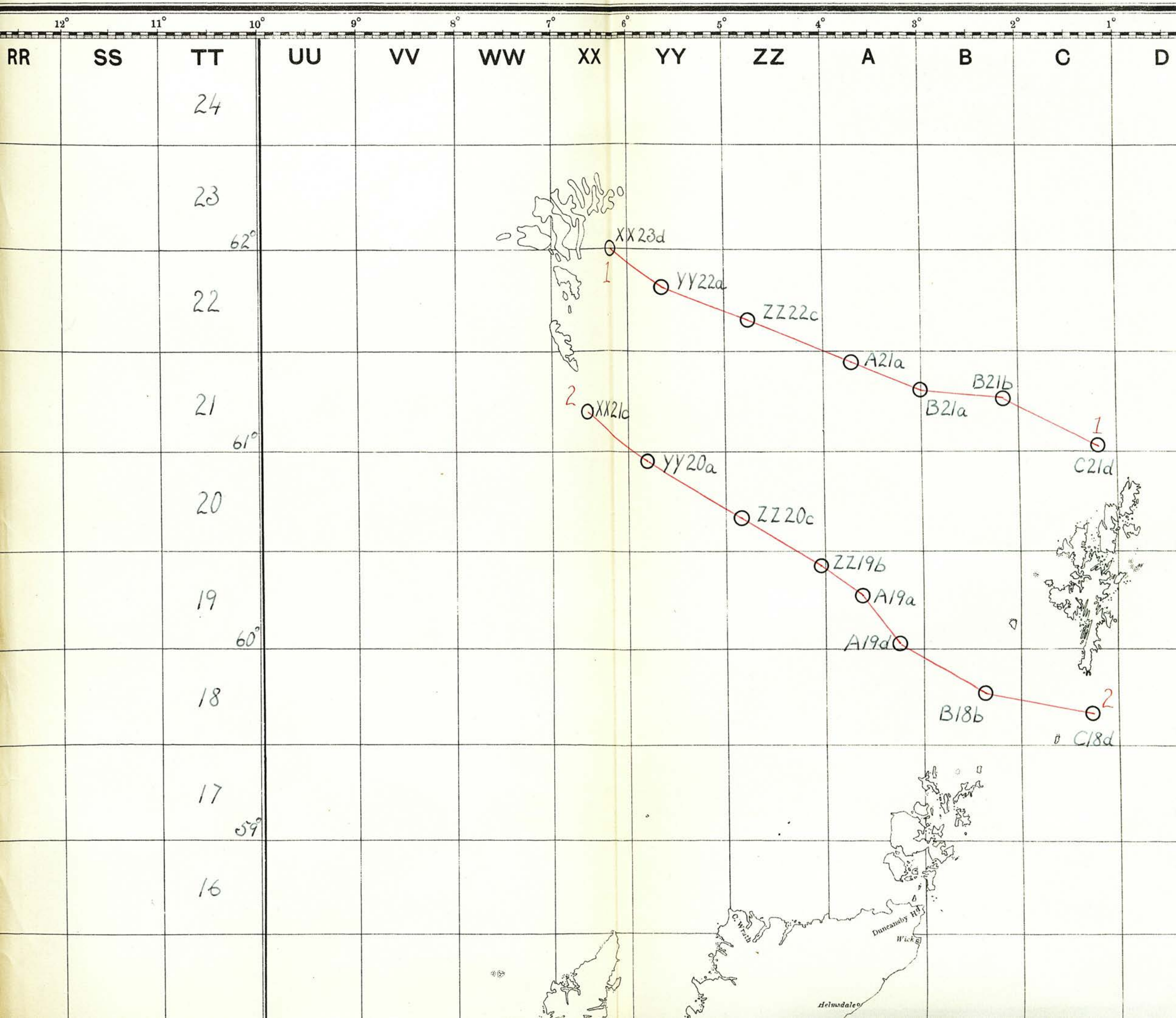
The maximum salinity on the northern section is 35.34 $^{0}/_{00}$, on the surface at C21d, the eastmost station, which was worked ten days prior to/

FIGURE 10.

FIGURE 10.

POSITIONS OF SECTIONS,

FAROE-SHETLAND CHANNEL, 1912.



to the other stations on VS(12)1. At 20 m. salinity falls to 35.23 ‰ and in lower levels the value is even less. What may more confidently be regarded as the nucleus of the Atlantic stream is the 50 m. column of 35.32 ‰ water in the surface layers of B21b, a station in the centre of the body of high-salinity water.

On the southern section the maximum is 35.39 ‰, a value which occurs at two stations, namely, in the upper 20 m. of ZZ19b and at the surface of A19a. These maxima are exceeded, in the case of the northern section, in five of the previous years (whether 35.34 ‰ or 35.32 ‰ be regarded as the maximum) and in the case of the southern section in only one (see Table II).

The stations at which maximum salinities occur in 1912, namely, at B21b and ZZ19b/A19a, are those at which highest salinities were most frequently found in spring over the period 1903-11. C21d, which may also claim maximal salinity in 1912, was less often the site of the nucleus of the Atlantic stream.

In respect of the depth of the water of highest salinity also, 1912 is in conformity with the majority of the previous years. The maximum depth attained by the Atlantic water in 1912 is approximately 400 metres on both sections. For the northern section, this is somewhat deeper than usual, and for the southern, on the other hand, slightly less than usual. As compared with 1911, however, the depth of the Atlantic water in 1912 is less by 150 metres.

Both north and south the Atlantic stream in 1912 is for the most part in a compact body on the edge of the Scottish Continental Shelf. A thin layer of high salinity water, however, stretches west in the uppermost layers to ZZ22c on VS(12)1, and on VS(12)2 to YY20a, where indeed, there is a minor maximum of salinity reaching 35.32 ‰.

As in 1911, the water on the Faroe Shelf, namely, at the three westmost/

westmost stations on the northern section and at the two westmost on the southern, is of lower salinity than the Atlantic Stream. Salinity, moreover, varies little with depth under the thin surface layer of Atlantic water.

On the eastern side of the Atlantic water, also, salinity is less. On the northern section, the eastmost station C21d has, except for the surface observation, salinities less than $35.25^{\circ}/oo$, and at 30-50 metres only $35.19^{\circ}/oo$. On the southern section, the decrease in salinity eastwards from the Atlantic stream is both greater and more abrupt. In the 20-mile interval between A19a and A19d salinity falls from over $35.34^{\circ}/oo$ at the former to $35.10^{\circ}/oo$ at the latter, the extreme difference being at the surface, where $35.39^{\circ}/oo$ is registered at A19a and only $34.97^{\circ}/oo$ at A19d. The Atlantic stream is thus very sharply bounded by much fresher water on the east on the southern section. This hydrographic condition is similar to that found in the same locality in May 1911, and is to be attributed to the like cause, namely, the presence of north-west Scottish coast water streaming north-eastwards from the vicinity of the Butt of Lewis. The fact that this water in 1912 is further west on the southern Faroe-Shetland line of stations than in 1911, when the contrasted stations were A19d and B18b, would seem to mean that the Atlantic stream offers less resistance to the westward spread of fresh water in 1912. In this respect also, then, the Atlantic stream in May/June 1912 is inferior to that in May 1911.

The greater restriction of the eastern flank of the Atlantic stream makes it even more improbable in 1912 that this water enters the North Sea by way of the Orkney-Shetland passage. This conclusion is supported by the fact that at the bottom at C18d there is water of temperature less than $8^{\circ}C$. This colder layer would be swept away if there were an easterly movement here from the Faroe-Shetland Channel into /

into the North Sea.

Below the Atlantic water on both sections in 1912, the deepest parts of the Channel are occupied by fresher water of precisely the salinity, 34.92°/oo, which generally characterises the bottom Norwegian Sea water. At the upper surface of this bottom water type, salinity, as in 1911, is slightly less, there being observations of 34.90°/oo both north and south.

On the northern section, the upper limit of the bottom water is approximately 300 metres below the sea surface, and on the southern, 450 metres. The former depth is 200 metres less than on the corres-:ponding northern section in 1911. The southern sections for the two years are of course not directly comparable, the bottom water in 1911 being unusually saline. As compared with the level of the upper limit of the bottom water in spring from 1903-11, that on the northern section in 1912 is rather shallower, and on the southern, rather deeper than usual.

Temperature.

High temperatures are associated with high salinities in the northern part of the Faroe-Shetland Channel in 1912. Not only is the Atlantic water warmest, but maximum temperatures are registered in the water of maximum salinity. Higher temperatures, moreover, are reached than in May 1911. On the northern section, the upper 100 metres at B21b (where the nucleus of high salinities occurs) have temperatures exceeding 9°, with a maximum of 9.45°C. at 10 metres. At C21d, which has an isolated high salinity at the surface with temperature 8.80°C. there are observations slightly exceeding 9° at 10 metres and 20 metres, but the general course of the 9°C. isotherm on VS(12)1 supports the contention, based on salinity distribution, that B21b is the site of the nucleus of the Atlantic stream.

On the southern section, the maximum temperature surpasses 10°C.

at/

at 10 and 20 metres on ZZ19b. The temperature maximum is thus slightly deeper than the salinity maximum. Not only is the maximum higher, but the cross-sectional area of over 9°C. water is larger on the southern section than on the northern. This is analogous to the greater extent of water exceeding 35.30°/oo in salinity on the southern than on the northern section, for the 9°C. isotherm and the 35.30°/oo isohaline are fairly closely associated on both. In like manner the 35.25°/oo isohaline in its deeper parts on both sections is linked with the 8°C. isotherm, while in the upper layers it lies in water warmer than 8°C. These are higher temperatures than were found on Table IV to be generally associated with the 35.25°/oo iso-:haline.

Westwards of the Atlantic stream, temperatures on the Faroe Bank mark the water in this region as being distinct from the former, there being little range as between surface and bottom. Whereas in 1911 this water had a temperature of from 6°C to 7°C. in 1912 the range is from 7°C. to 8°C.

On the south-eastern flank of the Atlantic stream also, temperat-:ure conditions are characteristic. At and east of A19d, temperature is uniform at less than 9°C. and more than 8°C. In 1911 this flanking water was cooler than 8°C. Thus both the Atlantic stream and the fresher waters on either side of it are warmer than in 1911. The three weeks interval between the dates of working in the two years (9-13/5/11 and 30/5-2/6/12) may, however, account for the disparity in temperature.

The fresher water in the trough of the Channel is, on the other hand, of the same temperature as in 1911 and indeed as is usually found. Zero and negative temperatures occur in the deepest layers and the upper limit of this fresher water is approximately 3° on both northern and southern sections.

Immediately/

Immediately above the bottom type, however, the 35.00^0/oo iso-:haline shows slightly higher temperatures than usual, but the relation-:ship of the two sections is normal, for the 35.00^0/oo isohaline is in rather warmer water, 4-5^{0}C. in the southern section than on the northern, where it is associated with 4-5^{0}C and less.

Hydrographic conditions in the Faroe-Shetland Channel in May/June 1912 are further illustrated by the horizontal charts HC(12)1-5 which are constructed from the same material as forms the basis of the vertical sections.

At all five places depicted, the Atlantic water is clearly seen to occupy the south-east side of the Channel, while the tapering north-eastwards of the bands of high salinity and temperature shows the diminution in volume of the Atlantic water as it traverses the Channel. The reason for this decrease is suggested by charts HC(11)3-5 partic-:ularly, in which a lobe of fresher cooler water pushes southwards in the centre of the Channel as in 1911. This fresh cool water, however, reaches lower latitudes in the Channel in 1912 than in 1911, showing further the poverty of the Atlantic stream in 1912 as compared with the previous year.

On HC(12)1-3 the function of the fresher water at A19d as an effective bar to the passage eastwards of the Atlantic water along the line of the southern section into the North Sea becomes even more apparent.

While much of the preceding, in bringing out the characteristics of the hydrography of the Faroe-Shetland Channel in 1912, gives promin-:ence to the differences between this year and 1911, the T-S diagram for 1912 shows that essentially the same elements underlie hydrographic conditions in both years. The differences are of degree, not kind.

In/

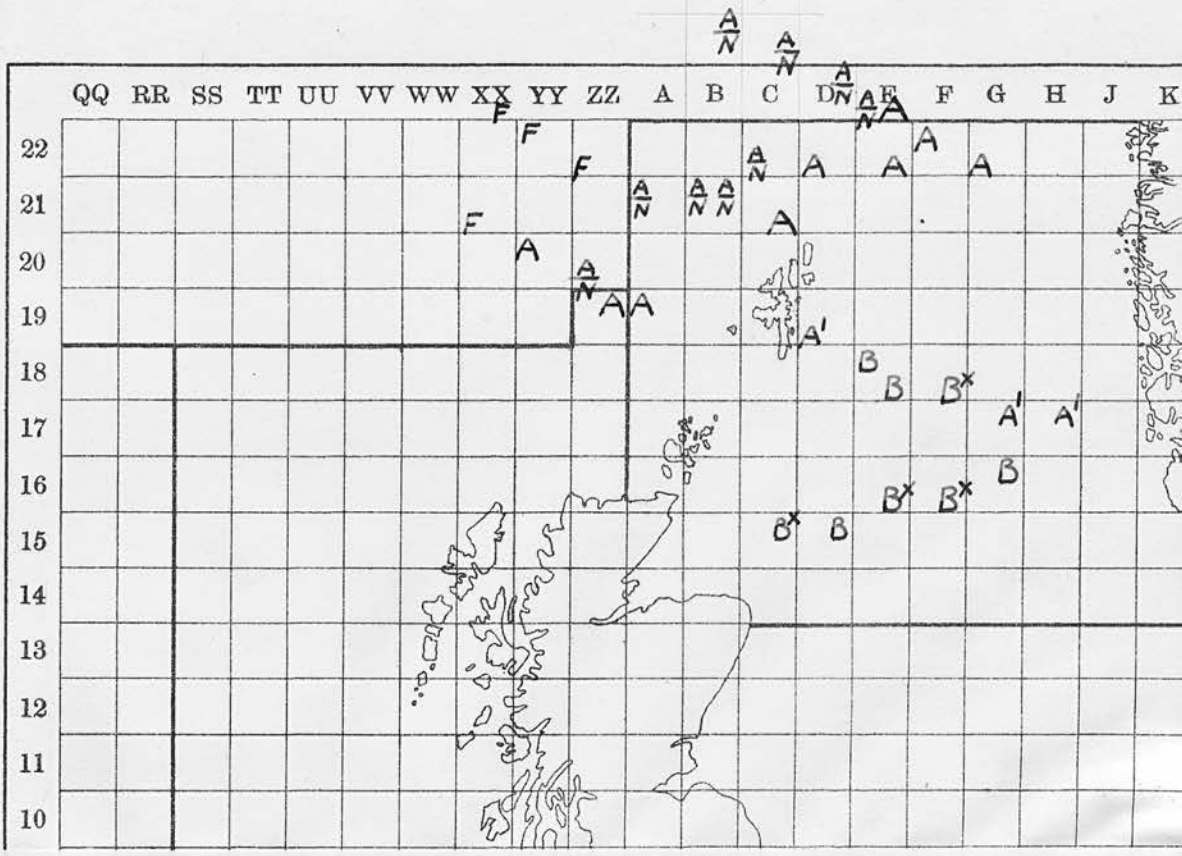


Figure 11.

Distribution of Water-Types, May/June 1912.

Salinity and temperature of the water-types shown on Figure 11, together with the positions and dates of the stations whose T-S curves make up the groupings which represent the above types.

A

(35.25-.35°/oo x 8.9°C)

TS(12)1

4	YY20a	1/6
7	ZZ19b	2/6
9	A19a	2/6
14	C21d	21/5

TS(12)2

7	E23d	25/5
8	F22a	25/5

TS(12)2a

2	D22c	25/5
3	E22d	25/5
4	G22c	25/5

A/N

TS(12)1

6	ZZ20c	2/6
8	A21a	31/5
11	B21a	30/5
12	B21b	30/5

TS(12)2

2	B24b	26/5
4	C24d	26/5
5	D23b	26/5
6	E23c	25/5

TS(12)2a

1	C22c	25/5

F

(35.20°/oo x 7-8.5°C)

TS(12)1a

1	XX23d	31/5
2	XX21c	1/6
3	YY22a	31/5
5	ZZ22c	31/5

A'

(35.25-.30°/oo x 7.5°C)

TS(12)3

24	D19c	19/5
34	G17b	18/5
36	H17b	18/5

B

(35.00-.25°/oo x 6.7°C)

TS(12)3a

×19	C(15)b	14/5
28	D15b	15/5
29	E18a	19/5
30	E18d	19/5
×31	E16d	15/5
×32	F18d	18/5
×33	F16d	15/5
35	G16b	18/5

25-30

In general lay-out TS(12)1 and 1a resemble quite closely TS(11)1 and 1a. In both, the form of the mass of curves is determined by a concentration of depth-marks indicating Atlantic water and joined by an oblique series of curves to a second group of points representing the bottom Norwegian Sea type. Beyond this, however, TS(12)1 and 1a show the distinctive character of hydrographic conditions in 1912.

Whereas in 1911 the Atlantic group is a more or less upright block constituting a definite entity with a distinct lower boundary from which the line of mixing proceeds, in 1912 the depth marks representing Atlan-:tic water form an elongated group which produces upwards the rectilinear axis of the line of mixing. The significance of this contrast is evident. In 1912 the Atlantic water is not of strongly marked character, and is influenced to such an extent by the bottom water that the grad-:ation from one type to the other is almost complete. The smaller cross-sectional area of Atlantic water in the Faroe-Shetland Channel in 1912 as compared with 1911 may not, therefore, be due to a diminution in the supply of Atlantic water, but to an increase in volume of Norwegian Sea water in the Channel, restricting the entry of Atlantic water and mixing largely with that which has gained entry. At the same time the above two conditions may be complementary, the opposing water masses together forming, as it were, a constant, a decrease in one being followed by, or even inducing, an increase in the other.

While the Atlantic cluster of depth-marks is not well-defined as in 1911, it is quite possible to classify certain curves as of Atlantic type in their upper parts. The positions of these are indicated on Figure 11 by the letter A, and where bottom Norwegian Sea water under-:lies the A type, by $\frac{A}{N}$. As mentioned earlier, the bottom Channel water is of typical salinity and temperature in 1912.

As in 1911, there is a group of curves with low range of salinity and temperature: these are plotted on TS(12)1a and represent stations on the Faroe shelf (F on Figure 11). As previously stated, temperature is/

is higher by 1° than in 1911; salinity, also, is slightly greater. Not only is this so, but again unlike 1911, the concentration of points does not fall quite on the Atlantic-Norwegian Sea line of mixing, surface temperature in the F type being higher than would be produced in water of this salinity by the above mixing process. This Faroe-type appears therefore to have been formed earlier than the time of working the section and to have lain more or less quiescent, allowing insolation to raise surface temperatures.

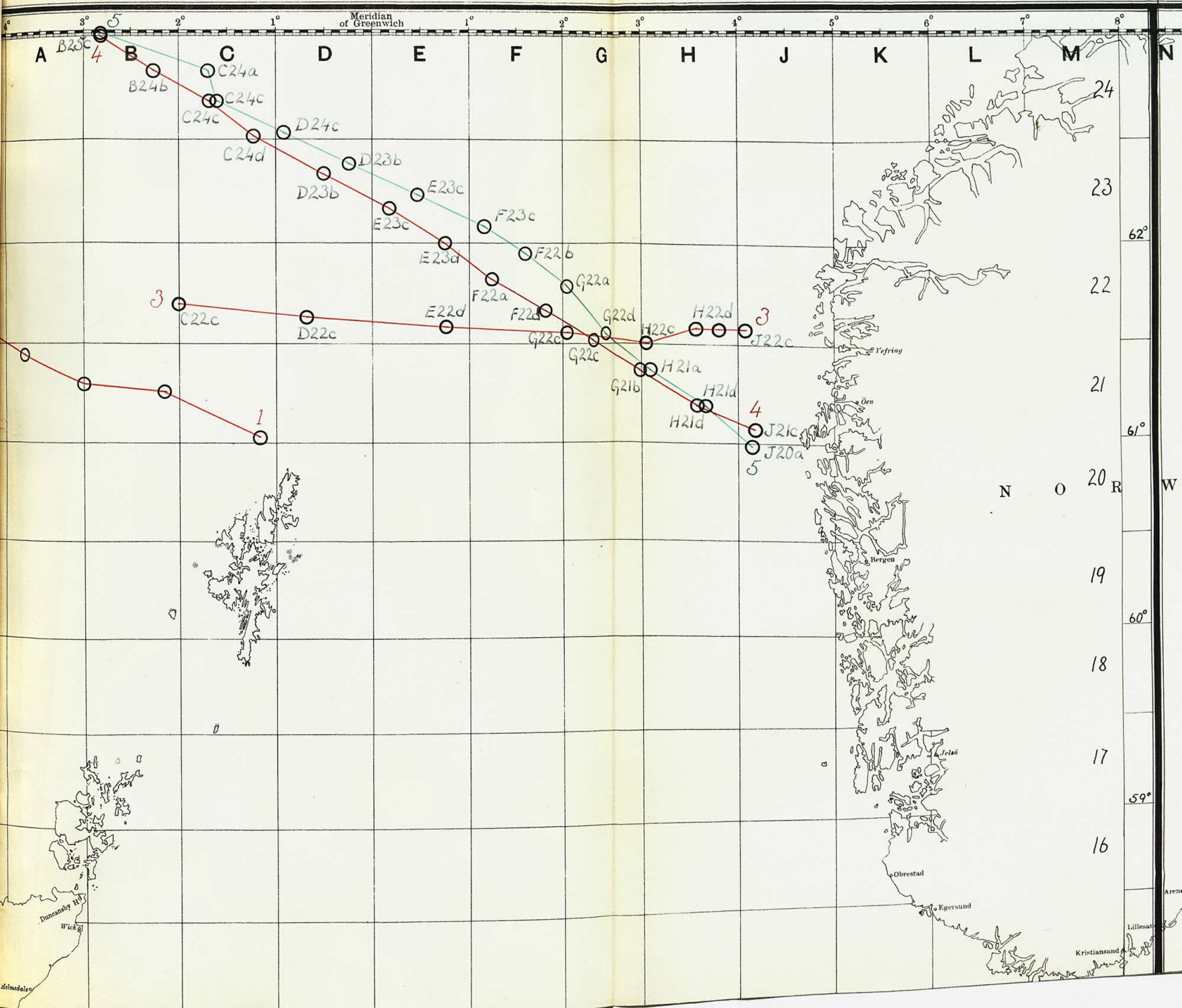
The broad characteristics of the hydrography of the Faroe-Shetland Channel in May/June 1912 as compared with May 1911 are, then, the diminished volume of Atlantic water, the greater extension upwards of bottom Norwegian Sea water, and higher temperatures in the upper layers.

FIGURE, 12.

FIGURE 12.

POSITIONS OF SECTIONS

SOUTHERN NORWEGIAN SEA 1912.



SOUTHERN NORWEGIAN SEA.

The same line of Scottish stations as was worked in 1911 was again laid down in the Southern Norwegian Sea between the 21st and 26th of May 1912. Two Norwegian lines of stations are also avail-:able, for the 24-26th May and 28-30th May respectively. Vertical sections have been constructed from these three lines of stations, the positions of which are shown on Figure 12. The Norwegian data obtained between the 24th and 26th May, being more nearly contempor-:aneous with the Scottish data, are used with the latter in the construction of horizontal charts and T-S diagrams.

The cross-sectional area of Atlantic water on VS(12)3, as bounded by the 35.25 $^{0}/oo$ isohaline, is 44 Km^2, or almost equal to the sum of the areas $(21 + 24\ Km^2)$ on the two Faroe-Shetland Channel sect-:ions. This relationship appears somewhat extraordinary. There is a difference, though not unduly large, between the dates of working the stations in these two regions, namely, 25-26/5/12 in the case of the Southern Norwegian Sea and 30/5-2/6/12 in the case of the Faroe-Shetland Channel. Two explanations of the large relative amount of Atlantic water in the Southern Norwegian Sea present themselves. First, that there was a sharp decrease in the volume of the Atlantic stream between the 25-26/5 and 30/5-2/6, and second, that the Atlantic stream is shown to a greater extent than usual in longitudinal section on VS(12)3.

In this connection it must be noted that in Table V there are two years which are analagous to 1912 in respect of the relationship of the volumes of Atlantic water in the Faroe-Shetland Channel and Southern Norwegian Sea. In 1906 the cross-sectional area of over 35.25 $^{0}/oo$ water in the Southern Norwegian Sea in April, namely, 52 Km^2 was/

was large in proportion to that in the Faroe-Shetland Channel in June, namely, 55 Km^2 ($11 + 44$ Km^2). In 1909, also, the area in the former region was 59 Km^2 in May, compared with 57 Km^2 ($12+45 Km^2$). in the Faroe-Shetland Channel in June. In April in the latter region the cross-sectional area was 145 Km^2 ($68+77 Km^2$).

It seems therefore that a diminution in the volume of the Atlantic stream after April is not unusual.

While the cross-sectional area of Atlantic water in 1912 on the Southern Norwegian Sea section is <u>less</u> than that for the corresponding section in 1911, the area of highest salinity water (over 35.30°/oo) is considerably <u>greater</u> on VS(12)4 than on the similar Norwegian section in 1911. This would suggest that the volume of the Atlantic stream in the Southern Norwegian Sea <u>is</u> actually large in May 1912 and not only <u>apparently</u> so, as would be the case if VS(12)3 were simply a more longitudinal section than usual.

The maximum salinity observed in the Atlantic water in the Southern Norwegian Sea in 1912 is 35.37°/oo, on the surface at D22c, a normal position. This maximum, however, is higher than that on either of the Faroe-Shetland Channel sections in 1912 and indeed ranks second in the series of maxima for the Southern Norwegian Sea from 1903-1911 (see Table VI). This circumstance also suggests that the Atlantic water in this region in May 1912 belongs to a more powerful pulse than is found in the Faroe-Shetland Channel in May/June of the same year.

The Atlantic water in 1912 is in the usual position, namely, on the 40 mile-wide strip of Continental Shelf between D22c and E22d on VS(12)3 and on the spur of the shelf on VS(12)4 and 5. Westwards from the Shelf on VS(12)3 the Atlantic water quickly thins out to a mere surface flake at C22c. The influence of the large amount of

bottom/

bottom Norwegian Sea water in the Faroe-Shetland Channel in 1912 is indicated here, for in 1911 the Atlantic water was 125 m. deep at C22c. Eastwards from the main body of Atlantic water, the limiting 35.25°/oo isohaline reaches to G22c on VS(12)3, while in 1911 it attained to H22c, a station 29 miles further east. This is a corollary of the fact that there is a smaller cross-sectional area of Atlantic water on the Southern Norwegian Sea section in 1912 than in 1911.

Temperature conditions in the Atlantic water resemble those found in 1911. The maximum of slightly over 9°C. is associated with the maximum salinity at D22c and most of the high salinity water has a temperature exceeding 8°C. and practically none less than 7°C. The lowest temperatures in the Atlantic water, also, occur on the under side of the eastern lobe.

The great depths below the Atlantic water to the west are occupied by bottom Norwegian Sea water of 34.94°/oo salinity, and temperatures from 4°C. to -1.05°C. Below the western flank of the Atlantic water on VS(12)4 and 5, salinity decreases irregularly to a level indicating bottom Norwegian Sea water, but even in the great depths isolated bodies of higher salinity water occur. The temperature of this abnormal water is, however, similar to that of the bottom Norwegian Sea type.

Above the Atlantic water in the east, fresh Baltic water spreads its influence as far west as G22c on VS(12)3 and on VS(12)4 and 5, further west, to about 1°30'E. - 30 miles further west than in 1911. This is probably accounted for by the less volume of Atlantic water present in 1912. Temperature in the Baltic water is less erratic in 1912 than in the previous year.

Underlying/

Underlying the Atlantic water and its continuation eastwards in a ridge of higher salinities to the Norwegian Continental Slope, there is, as in 1911, fresher cooler water on all three sections, VS(12)3, 4 and 5. On VS(12)3 salinity is 35.07°/oo-35.10°/oo at the bottom, with temperatures just under 6°C., but on the other two sections, lower values of both salinity and temperature are recorded.* This fresh, cooler water therefore appears to be moving southwards and undergoing a rise of temperature and salinity from contact with the Atlantic water which is in its turn, as previously noted, cooled in the part nearest to the bottom of the Norwegian Trench.

Even with the inclusion of the data comprised in VS(12)4, the Southern Norwegian Sea is inadequately covered by the horizontal charts, HC(12)1-4. The axis of the Atlantic stream can, however, be traced from the Faroe-Shetland Channel eastwards to 62°N., 1°E. and at 100 m. (HC(12)4) sending a branch into the North Sea. At 200 m., HC(12)5, apparently all of the Atlantic stream turns south:wards towards the Viking Bank.

The Scottish and contemporaneous Norwegian data for the Southern Norwegian Sea in 1912 are plotted on TS(12)2 and 2a. The Scottish curves are in green on the transparency, and the Norwegian on TS(12)2, the separation being made in order to avoid over-crowding.

In broad outline, the T-S curves for 1912 resemble those for 1911 on TS(11)2 and 2a. There are the same elements in the structure of/

* The observation of 34.69°/oo at the bottom of F22b on VS(12)5 is almost certainly erroneous, for such a salinity creates a very definite inversion of density here.

of both, namely (a) The concentration of points at 35.30°/oo x 8-9°C., representing Atlantic water, (b) The grouping of depth-marks indicating bottom Norwegian Sea water with salinity round 34.92°/oo and temperature from 3°C. to -1°C. (c) A line of mixing joining (a) and (b) and finally (d) a set of curves with great extension to the left owing to the presence on the surface of these stations of Baltic water. The distribution of the stations making up the groups (a) and (b) is shown by the indices A and $\frac{A}{N}$ on Figure 11.

While the essentials of the hydrography are similar in 1911 and 1912, there is, however, a point in which TS(12)2a differs from TS(11)2a. The bottoms of curves 4,5,6,7 and 9 are clustered about the line of mixing (c), indicating that the bottom water at these stations is a product of Atlantic and bottom Norwegian Sea water. This is as in 1911. The actual temperature and salinity of the mixture in 1912 is, however, ·5°C. and .10°/oo less than in 1911, that is, there is a smaller proportion of Atlantic water in the mixture in 1912 than in 1911. In this respect, then, the poverty of the Atlantic stream in 1912 as compared with 1911 is further reflected.

The curves influenced by Baltic water differ in detail from their analogues in 1911, but in view of the erratic character of this water, such differences may be regarded as minor and unimportant.

The Southern Norwegian Sea in May 1911 is therefore characterised by a decrease as compared with May 1911 in the Atlantic water and by the presence of a greater amount of this water-type than occurs on either of the Faroe-Shetland Channel sections, a condition contrasted to that in 1911 when the amounts on all three sections were similar.

FIGURE 13.

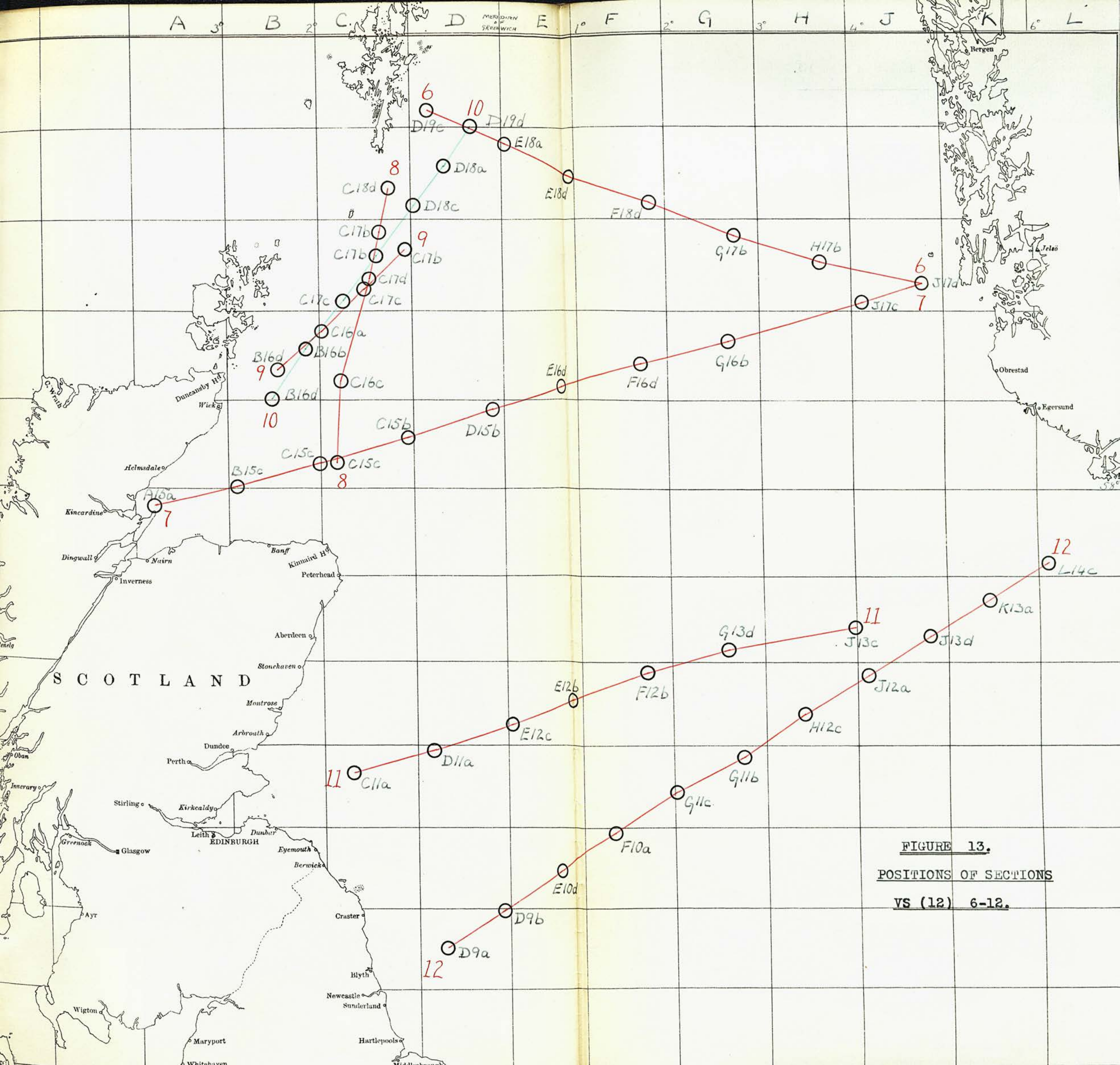


FIGURE 13.

POSITIONS OF SECTIONS

VS (12) 6-12.

Substitute for page 66

NORTHERN NORTH SEA.

Data are somewhat scanty in the Northern North Sea in 1912. The North-Western area was visited only three times, but on the other hand, two sections cross the North Sea from Scotland to Norway. The five sections can be located on Figure 13.

May. The first section of the year, VS(12)6, is for May, and extends from Shetland to Norway. Saltest water is to be found at H17b, where, at a depth of from 100 - 200 metres salinity reaches 35·30‰ in association with a temperature of 8°C. Round this nucleus is a mass of water of salinity above 35·20‰ which spreads down into the deep Norwegian Trench and west across the North Sea Plateau almost to F18d. Only at the eastern and western extremities of this water does the temperature fall below 7°C. Salinities of 35·20‰ appear again in the west, but almost half of this water is cooler than 7°C. and the maximum salinity is only 35·23‰. The water on VS(12)6 most nearly related to the Atlantic type in the Faroe-Shetland Channel and Southern Norwegian Sea is, therefore, that with its nucleus on the edge of the Continental Shelf in the east.

Hydrographic observations in 1911 do not extend to the eastern side of the Northern North Sea as in 1912, with the result that the two years are not directly comparable in respect of conditions off the Norwegian coast. In both 1911 and 1912, Atlantic water extends across the Southern Norwegian Sea and in this respect the two years resemble each other and conform to what appears to be normal hydrographic conditions for the area.

In the Northern North Sea in 1911 the charts show salinities of Atlantic character in the region immediately east of Shetland. There are no data to show what the conditions are on the eastern side of the Northern North Sea at the same time.

In 1912 the data cover all of the belt between Shetland and Norway and reveal the presence of high salinity water on the east side of the Northern North Sea, while the area just east of Shetland has relatively low salinities.

From these circumstances we can suppose either

(1) that in 1911, though there are no data to show it, there is Atlantic water in the east side of the Northern North Sea as well as on the west. In this case, 1911 would differ from 1912 only in having a more powerful influx of Atlantic water to the east side of Shetland.

or (2) that the Atlantic water entered the west side of the Northern North Sea in 1911, the east side in 1912.

The second supposition is to be supported on the following grounds:-

(a) If there were Atlantic water on the east side of the Northern North Sea in 1911 in addition to that which the charts show in the area east of Shetland, the total volume of Atlantic water in the Northern North Sea would be most extraordinarily large.

(b) Previous investigations as well as the present show that normally the influx of Atlantic water to the North Sea is in one branch only, and that lying on the east side of Shetland. The high salinity water in this position in 1911 (shown by the charts) thus probably represents the entire Atlantic influx at this time.

(c) In support of the contention that the high salinity water on the east side of the Northern North Sea

Page 67A

in 1912 is indeed the Atlantic influx in an unusual position, it is to be noted that the charts show that the circulation further south in the Northern North Sea at the same time is also abnormal.

Hence the conclusion is, in spite of the lack of data for the east side of the Northern North Sea in 1911, that the Atlantic influx to the North Sea in 1912 was of unusual character and therefore differed from that in 1911 in that it entered the east side of the Northern North Sea rather than the west.

With regard to the fresher water from the stream along the Norwegian coast, VS(12)6 show this water-type spreading out across the Northern North Sea in a layer 50 metres deep almost to E18d, while at J17d this water reaches a depth of 150 metres. This westerly extension of fresh water is greater than that observed further north, in the Southern Norwegian Sea, in either 1912 or 1911.

In the extreme west of VS(12)6 the surface temperature

- - - - and so on - - - - (See second par. of page 67 in thesis).

Table VIII

-- Salinities are lower in 1911 than in 1912 & the water-column to be deleted ?

Sea in 1912 follows a different course from that in 1911. In 1911 the track pursued is that regarded as normal, namely, along the east side of Shetland, whereas in 1912 the high salinity water passes southwards on the east side of the Northern North Sea Plateau.

On VS(12)6, fresh water from the stream along the Norwegian coast spreads out across the Northern North Sea in a layer 50 metres deep almost to E18d, while at J17d this water reaches a depth of 150 metres. This westerly extension of fresh water is greater than that observed further north, in the Southern Norwegian Sea, in either 1912 or 1911.

In the extreme west of VS(12)6 the surface temperature exceeds 8°C. and the bottom 7°C. The warmer surface layer is associated with lower salinities, both of which factors point to the presence here of north-west Scottish coast water which has rounded the north of Shetland. The higher temperatures on the bottom at D19c than further east can be accounted for by tidal mixing.

Station E18d is comparable with one in the same sub-rectangular area at the same date in 1911. The following are the observations.

Table VIII.

Hydrographic Observations at Station E18d on the 19th May in 1911 and 1912.

E18d 59°31'N. 0°37'E. 19/5/11			E18d 59°44'N. 0°56'E. 19/5/12		
Depth (metres)	Tempr. (°C.)	Salinity (°/oo)	Depth (metres)	Tempr. (°C.)	Salinity (°/oo)
0	8.06	34.97	0	7.60	35.08
10	8.13	34.99	10	7.66	35.10
20	6.87	35.03	20	7.66	35.10
30	6.67	35.03	30	7.66	35.10
50	6.40	35.05	50	7.53	35.16
70	5.99	35.05	70	6.72	35.21
100	5.94	35.05	100	6.50	35.21
125	6.01	35.08	118	6.48	35.19

Salinities are lower in 1911 than in 1912 and the water-

column/

column as a whole cooler, though the upper 10 metres are warmer than in 1912. (The presence of north-west coast water is indicated in the upper 10 metres, which are less saline than the underlying layers). In both years there is a discontinuity layer: in 1911 this occurs between 10 and 20 metres and in 1912 between 50 and 70 metres. In 1911 salinity in the upper layers is reduced, it would seem, by north-west coast water: in 1912, however, VS(12)6 shows that the freshen-:ing source is Continental water. In both years salinities are highest in the bottom layers, but whereas in 1911 these salinities are not so high as those in the upper 50 m. of E18d in 1912, the bottom water in this latter year shows a salinity related to the Atlantic type. In May 1911 salinities were high west of E18d and in a lobular area south from the east side of Shetland: in May 1912 the corresponding Atlantic influence is spread over a greater area and has its axis not west of E18d but far to the east.

South of the previous sections but with similar data is the parall-:el VS(12)7 which stretches from Tarbet Ness to Utsire.

There are two foci of salter water, with salinity maxima reaching the moderate values of 35.17°/oo and 35.19°/oo, at D15b and G16b respectively. The former body of salt water extends west on the bottom to C15b, and the latter east on the bottom and down into the Norwegian Trench at J17c. Between these two regions of salter water, salinity falls to below 35.00° /oo in the upper half of the water-column at E16d and is less than 35.10°/oo round E16d and F16d.

In the Moray Firth, salinity is uniform from surface to bottom and increases eastwards to C15c, where, in the upper layers, it remains steady to C15b and then falls off again. The fresh water in the east spreads only to G16b - not so far west as on VS(12)6, but still occupying a considerable depth (150 m.) at J17c and J17d.

Temperature/

Temperature is highest in the upper layers in the Moray Firth, doubtless owing to the influence of the neighbouring land. From C15b eastwards the 7° isotherm runs horizontally at 50 metres but passes out to the surface at about 3°E., that is, the Norwegian coastal water is colder than the fresh water round E16d. The manner in which the isotherm of 7° maintains a horizontal course through water of varying salinity suggests that these differences of salinity were established at an earlier date than was the temperature distribution and that the water-mass has been lying more or less quiescent, allowing temperature to become regularised. The 7° C. isotherm behaves in a somewhat similar manner in the middle and west of VS(12)6.

None of the high salinity water on VS(12)6 appears on VS(12)7; doubtless the spreading out of the Atlantic water westwards from the edge of the shelf in the east dissipates the vigour of the influx to such an extent that it is unable to penetrate as far south as VS(12)7. The absence of high salinity water from this section also precludes the possibility of the salt water on VS(12)6 having arrived there by a course south along the north-west of the Northern North Sea and swinging round to pass out of the North Sea along the Norwegian coast.

The next section to be considered is VS(12)8, which is the Aberdeen-Shetland line of stations, traversed about a fortnight after the lines constituting VS(12)6 and 7.

Salinity is highest, namely 35.16°/oo to 35.19°/oo at C17d and C17b, reaching a maximum of 35.21°/oo in the upper layers at the former station, where density inversion exists. Northwards, salinity falls off to 35.14°/oo and even 35.12°/oo at the bottom. Southwards from C17d the decrease is greater, salinities under 35.10°/oo supervening some 20 m. south of C17d. The position and lowness of the maximum/

maximum of salinity is strong indication that the Atlantic influence is not penetrating to the line of this section.

The isotherm of 8°C. slopes gently downwards from 50 metres in the south to 80 metres in the north, and its steady course through waters of differing salinity would indicate that circulation is very sluggish.

<u>June.</u> VS(12)9 crosses VS(12)8 somewhat obliquely, but comparisons between the two are nevertheless possible. At the common position, C17d, salinities have fallen in the 16 day interval, but at C17b, salinities of 35.21‰ appear. This station is 10 miles farther east than C17b on VS(12)8. The temperature of this water is only 6.98°C. in the bottom layers. It would appear therefore that a state of relative stagnation and lack of Atlantic influence persists here.

<u>November.</u> VS(12)10 is comparable in position to VS(12)8 and 9. While salinities are unchanged in the south, they have fallen in the north, the maximum, even at D19d, being only 35.16‰, and in the upper layers here, salinity falls to 35.05‰, possibly owing to the presence of some north-west coast water. Vertical convection currents appropriate to the season render the distribution of temperature and salinity very uniform.

Horizontal charts have been constructed to illustrate further the hydrographic conditions in May. The data for the Northern North Sea part of HC(12)1-4 are those which make up VS(12)6, 7 and 8. The time-interval between the data of the former two lines and the latter one is rather large - about 17 days, and must be borne in mind when considering the charts.

At/

At the surface and 20 metres the fresher Baltic water spreads to 1^{o}W., except at G16b, where the underlying salter water reaches to the surface, giving a false impression of a lobe of salt water pushing northwards.

At 50 and 100 metres, the underlying fundamental distribution of salinity and temperature appears. North of a line south-east from Shetland, salinity exceeds 35.20 $^{o}/oo$, with the maximum, as the sections show, in the east of H17b. In the centre of the Northern North Sea, a tongue of less than 35.15 $^{o}/oo$ water stretches north along 1^{o}E., but to the west of this, salinities are again higher, 35.10 $^{o}/oo$ 35.20 $^{o}/oo$. This picture is in complete contrast to that for the same area in May and August 1911.

On TS(12)3 and 3a are shown the curves for all the stations in the Northern North Sea in 1912. The curves on the transparency TS(12)3 relate to the stations constituting VS(12)6 and 7. This diagram will be examined first.

On TS(12)3 the bottoms of the curves can be divided into two groups, A$'$ with salinity and temperature of 35.25$^{o}/oo$-35.30$^{o}/oo$ and 7.5^{o}C. and B with 35.00$^{o}/oo$-35.25$^{o}/oo$ and 6-7^{o}C. A$'$ is the representative of the Atlantic water in the Northern NorthSea. The B group, with salinity limits so wide as hardly to constitute a type, is so named simply because it occupies the area covered by the B type in 1911. This B type in 1912 has not the same salinity and temperature as the B type which persisted throughout 1911. Here again is a difference between hydrographic conditions in 1911 and 1912. The distribution of the two water-types is plotted on Figure 11, the B type having a sub-division B^{x} where the surface layer is fresher.

The only concentration of points on TS(12)3a is that formed by curves/

curves 25, 26 etc, with very small range of temperature. This grouping is due to convection currents equalising conditions in October. The T-S diagram therefore adds nothing to what was shown by VS(12)8, 9 and 10.

MIDDLE NORTH SEA.

Only two lines of stations are available for this area in 1912, a Scottish and an English line, VS(12)11 and 12, both worked in June. The positions of these are shown on Figure 13.

June. The main feature of VS(12)11 is the extent of water of salinity exceeding 35.00°/oo which lies between E12b and G13d. At the latter station the uniformity of salinity is broken by an increase at the bottom to over 35.10°/oo. The block of over-35.00°/oo water has a temperature above 11°C. on the surface, 1° higher than that to east and west of it. West of E12b salinity decreases steadily, and while the temperature of the upper layers remains constant, the bottom increases from less than 7°C. at E12b to over 8°C. at C11a. The central area would thus appear to be relatively stagnant.

On VS(12)12 salinity is irregular. It increases from the English coast to F10a, falls off at the next station G11c, increases at G11b, falls off at H12c and increases again eastwards on the bottom, but on the surface continues to decrease, the upper layers here being of low salinity Continental water. The maximum observation, at J13d, rises to over 35.10°/oo, suggesting a relationship with the water of similar salinity on VS(12)11.

Temperature is highest on the surface in the west, unlike conditions on VS(12)11, and bottom temperatures are everywhere under 7°C., while the upper layers do not attain 10°C. between G11c and J13d. The temperature distribution is thus almost the converse of that on VS(12)11, a fact which suggests that these two sections cover hydrographically different regions.

The/

The Middle North Sea area of the horizontal charts HC(12)1-3 is constructed from the same material as are VS(12)11 and 12.

Salinity increases eastwards from the British coast to 1^{O}E. and for some distance beyond remains steady round $35.00^{0}/oo$, after which the Baltic water appears on the surface, and at a depth of 50 metres some water over $35.10^{0}/oo$ in salinity lies east of the Fisher Bank. This salter water is probably related to the high salinity water found at the east side of the Northern North Sea in May.

The T-S curves for the two lines of stations dealt with above are plotted on TS(12)4a. The depth-marks at the bottoms of the curves show a marked grouping at $34.95^{0}/oo$-$35.15^{0}/oo$ and 6.5^{0}C. These are rather wide salinity limits, but inspection shows that a further sub-division is not possible, except to distinguish between those curves where salinity is constant with depth, and those with Baltic water on top. This is as well seen on the sections and horizontal charts. Though TS(12)4a shows only one bottom type of water, it does enable the composition of this water to be investigated. If the co-ordinates of the limits of this $34.95^{0}/oo$-$35.15^{0}/oo$ x 6.5^{0}C water be plotted on TS(12)2 it becomes evident that water of such characteristics can be derived from a dilution of the B type in the Northern North Sea in May by Baltic water.

TS(12)4 shows the curves for the remainder of the stations worked in the Middle North Sea and in respect of which sections and charts have not been constructed. These stations are shown on Figure 14. The diagram throws no light on the major circulation of the North Sea, but gives only details for scattered observations.

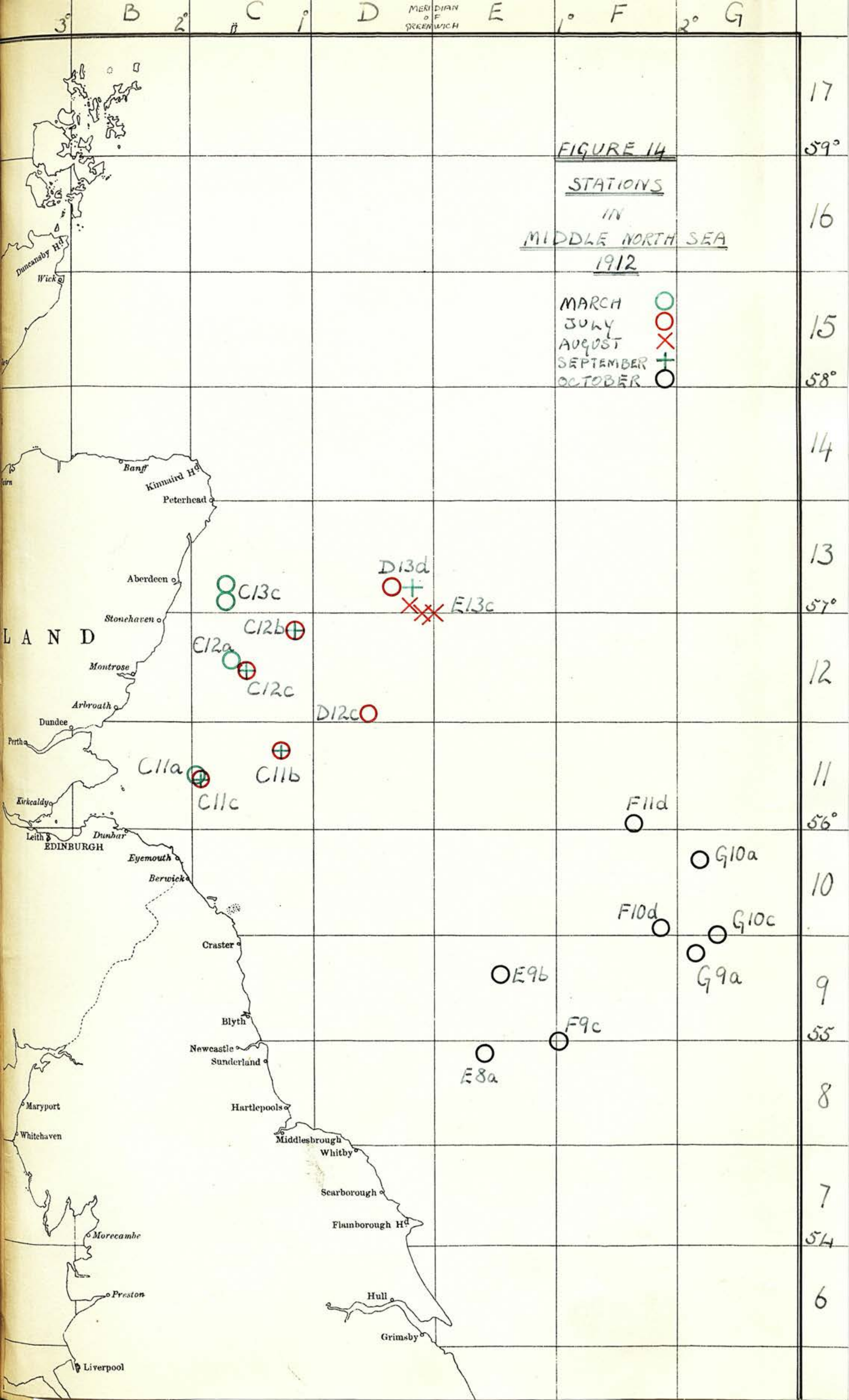


FIGURE 14
STATIONS
IN
MIDDLE NORTH SEA
1912
MARCH
JULY
AUGUST
SEPTEMBER
OCTOBER
MERIDIAN OF GREENWICH
B
C
D
E
F
G
3°
2°
1°
1°
2°
17
59°
16
15
58°
14
13
57°
12
11
56°
10
9
55
8
7
54
6
D13d
C13c
E13c
C12b
C12a
C12c
D12c
C11a
C11b
C11c
F11d
G10a
F10d
G10c
G9a
E9b
F9c
E8a
Duncansby Hd
Wick
Banff
Kinnaird Hd
Peterhead
Aberdeen
Stonehaven
LAND
Montrose
Arbroath
Dundee
Perth
Kirkcaldy
Leith
Dunbar
EDINBURGH
Eyemouth
Berwick
Craster
Blyth
Newcastle
Sunderland
Hartlepools
Middlesbrough
Whitby
Scarborough
Flamborough Hd
Maryport
Whitehaven
Morecambe
Preston
Hull
Grimsby
Liverpool

March. The March curves are numbers 1, 2, 3 and 8, which have each great uniformity of salinity and temperature, the latter being very low, 5.5° - 6.5°C. The station with highest salinity is number 8, which is east of May Isle, while that with lowest is off Aberdeen, and the others are, in order both of position and salinity, in sequence between these two. This decrease of salinity northwards is the opposite of what might be expected, and is probably due to some eddy-motion bringing salter water to C11a.

July. The July curves may be arranged in order of increasing salinity and expanding range of temperature as between surface and bottom thus - 12, 6, 4, 10, 18, 14. Reference to the positions of these stations shows that salinity and surface temperature increases, while the bottom becomes cooler, north-eastwards from St. Abbs Head.

August. The August curves, 15, 16 and 24 are very similar to each other, having high (over 13°C.) surface temperatures and bottoms between 7° and 8°C. These stations lie just north-east of the series worked in July and they thus continue the trend of temperature and salinity observed at that time. A steep temperature gradient exists at 30-50 m., there being a drop of temperature between these levels from over 12° to 8°-9°C.

September. The main feature of the September curves, 5,7,11, 13, 17 and 19, is the very limited range of temperature and salinity at each station, convection currents having reduced surface and raised bottom temperatures to a common level of about 11°C. These stations are again off the mid East Scottish coast.

October. The October curves, 28, 29, 31, 33, 34, 38, 39, 40, lie between 55°N. and 56°N. and 0°E. and 3°E. The three southerly stations, 25, 29, and 33, have the least range of temperature, and salinity is approximately $34.70^{\circ}/oo$. North of these, the temperature range and value of salinity increase to a maximum at numbers

27/

27 and 31, where salinity is $34.90^{\circ}/oo$ - $35.00^{\circ}/oo$, surface temperature $10.5^{\circ}C$. and bottom $7^{\circ}C$. The other stations are intermediate in position and hydrographic conditions. Here again, then, is an east-west junction between two types of water, analogous to that found in June. In July and September, a line with a similar contrast on either side of it lay meridionally off the Scottish coast. The centre of the Middle North Sea in 1912, therefore, appears generally to have higher salinity and surface temperature, but lower bottom temperature, than to the west and south of this area.

Summary of Hydrographic Conditions
in the North Sea in 1912.

A survey of the changes in hydrographic conditions throughout 1912 cannot be effected, on account of lack of data, but what material there is shows some striking differences from 1911. Chief of these is that in 1912 the axis of the influx of Atlantic water to the area lay on the eastern side of the Northern North Sea. The north-western area, normally the seat of the insetting Atlantic water, had only moderately high salinities.

The central area of the Northern North Sea was occupied in 1912 by water of similar low bottom temperature to, but of somewhat higher salinity than, that in 1911. In 1912 this central water did not spread so far north as in the previous year, the area between Shetland and Norway being occupied by modified Atlantic water.

THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS

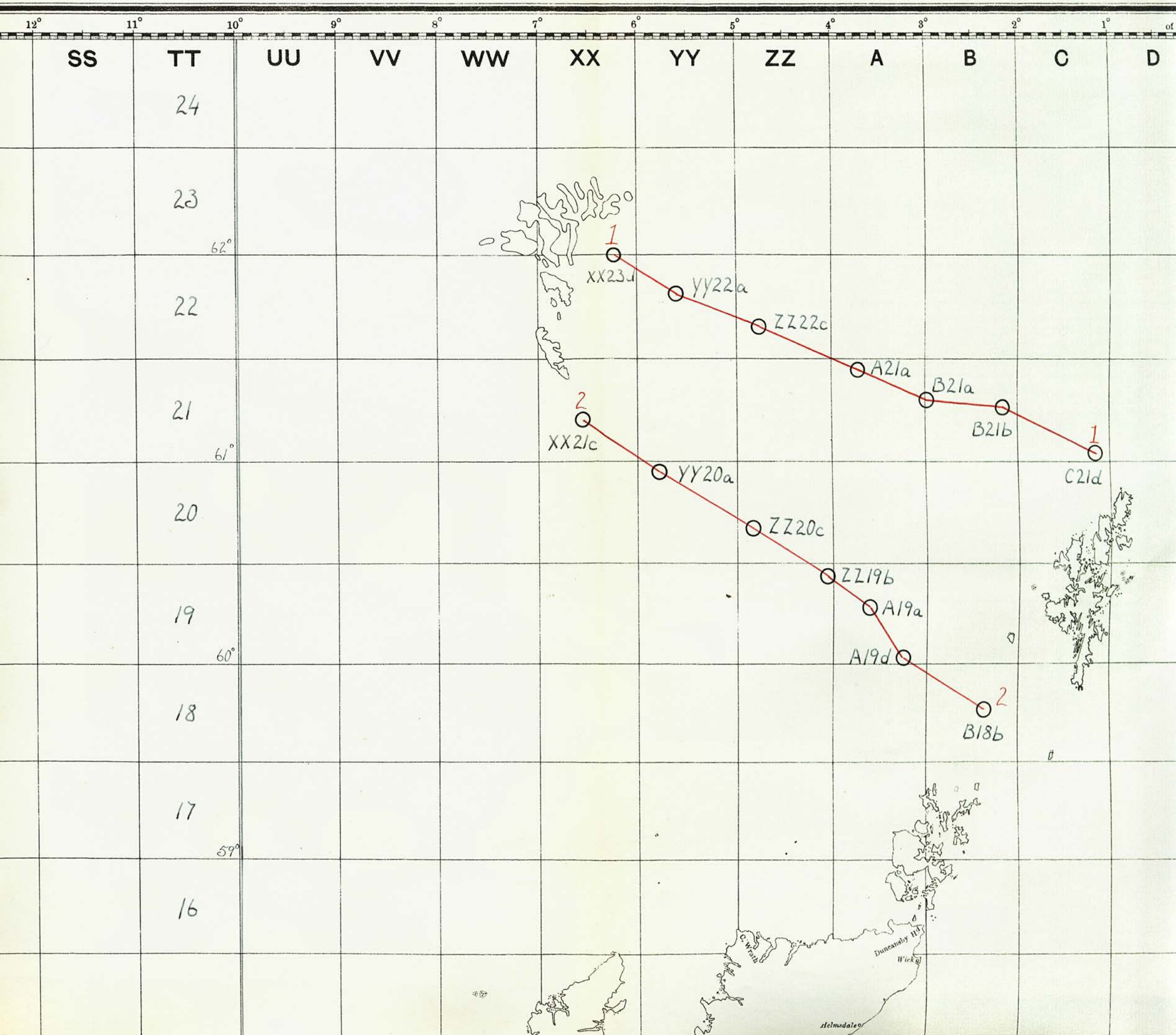
DURING THE YEAR 1913.

F I G U R E   15.

FIGURE 15.

POSITIONS OF SECTIONS.

FAROE-SHETLAND CHANNEL, 1913.



THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS DURING THE YEAR 1913.

THE FAROE-SHETLAND CHANNEL.

The sole hydrographic cruise in the Faroe-Shetland Channel in 1913 was made between the 9th and 13th of July, the usual two lines of stations, less C2ld, being traversed. Observations from the latter station on the 16th of July are utilised to complete the northern section, the positions of which and the southern section are shown on Figure 15.

Since both sections pertain to the month of July, the study of hydrographic conditions in the Faroe-Shetland Channel in spring, as made in respect of 1911 and 1912, cannot be extended to include 1913. Moreover, it is not possible to construct tables of hydrographic features in July of previous years, for the area was only once visited in that month in the period 1902 to 1912.

S a l i n i t y.

There is evidently more than twice as much Atlantic water on the southern section as on the northern, the cross-sectional areas of over 35.25°/oo water being 38Km^2 and 18Km^2 respectively. Such a disparity between the two sections is not unusual in spring, similar conditions occurring in 1906, 1908, 1909 (June) and 1910. These are years in which Atlantic influence in spring was below the average, and while this suggests that 1913 may fall into the same category, it must be remembered that, as pointed out in dealing with 1912, a more or less sharp decrease in the Atlantic stream not uncommonly follows a spring abundance.

The total area of Atlantic water on both sections in July is, however,/

however, below the average for the spring months as shown on Table I and also compares unfavourably with the cross-sectional areas found in August over the period 1902-1910. It appears highly probable, therefore, that 1913, like 1912, is a year in which the Atlantic stream in the Faroe-Shetland Channel is of less than usual volume.

In July 1913, as in the majority of instances, the nucleus of the Atlantic stream as indicated by maximum salinities is on the S.E. side of the Channel. The highest salinity on both sections is 35.32°/oo, a lower value than that generally found in spring between 1903 and 1912. On the northern section, the maximum occurs at all depths (bar 50 m.) of C21d, the eastmost station, and on the southern section in the lower 100 m. at A19a. The axis of the Atlantic stream is thus in a similar position to that commonly found in spring, namely, on the edge of the Scottish Continental Shelf.

On the northern section, however, there is a secondary nucleus of Atlantic water in the west, at ZZ22c, almost severed from the main stream in the east by the great diminution in depth of the high salinity water at A21a. On the northern section, indeed, the Atlantic stream attains a maximum depth of only 150-200 m. On the southern section, by contrast, the Atlantic stream is deepest in the centre of the Channel, sounding fully 300 m. Both of these maximum depths, and more particularly that for the northern section, are less than the average spring maximum.

While the maximum depth of the Atlantic water is greater in May/June 1912 than in July 1913, the stream in the latter season maintains a greater vertical extent in the west of the Channel than in May/June 1912 and indeed almost as great as in May 1911, a season of abundance of highly saline water. The Atlantic stream in July 1913 thus appears to be broader and shallower than is usual in spring.

A result of the greater breadth of the Atlantic stream in July 1913 is/

is that only the station nearest to Faroe on both sections shows the lower and uniform salinities analagous to those which in 1911 and 1912 characterise this locality.

Fresher water occurs also on the eastern flank of the Atlantic stream in the southern section, but not on the northern. At A19d on VS(13)2 the salinity in the upper 10 m. is 35.07°/oo, but from 50 m. downwards 35.25°/oo is exceeded. This is the same station as was occupied by the north-west Scottish coast water in 1912, but the freshening influence then was more powerful (the maximum salinity at A19d was only 35.10°/oo) than in July 1913. The absence of low salinities at the east end of the northern section in 1913 is doubtless related to the paucity of fresher water on the southern section at the same time. At the eastmost station on the southern section, B18b, salinity is uniform at 35.19°/oo to 35.17°/oo, except at 50 m., where 35.20°/oo is attained, suggesting that some Atlantic water may be penetrating eastwards at this level. Otherwise the fresher waters flanking the Atlantic stream on the south-east would seem, as in the two previous years, to preclude any entry of the high salinity water into the North Sea by the Orkney-Shetland gap.

In addition to the fresher water on both flanks of the Atlantic stream, there are lower salinities underneath it, flooding the deepest parts of the Channel. This underlying water is of the usual bottom Channel salinity, namely, 34.92°/oo, which proclaims its origin to be in the lower levels of the Southern Norwegian Sea.

On the northern section, this fresher water reaches to within 300 m. of the surface at A21a, but its influence is apparent also in the upcurving of the isohalines between this depth and the surface, almost dividing the high salinity water at ZZ22c from the main body of Atlantic water to the east.

On the southern section, on the other hand, the upper surface

of/t

of the bottom water is horizontal at 500 m., showing no tendency to push upwards into the Atlantic water.

Compared with the average depth found in spring over the period 1903-11 the upper limit on the northern section is nearer the surface, and in the southern section deeper, than usual. This condition holds also for May/June 1912.

The volumes of Atlantic and bottom Norwegian Sea water are thus broadly in inverse proportion on the two July 1913 sections. Such a relationship between these two water-types was suggested in discussing the hydrography of the Channel for 1912.

T e m p e r a t u r e.

Highest temperatures occur in the upper layers of the Atlantic water, but the association of high temperature with high salinity is not so close as in 1911 and 1912. The maximum temperature of 13.11°C on the northern section occurs at the surface of C21d, where salinity is highest, but on the southern section the maximum of 12.11°C. is at the surface at ZZ19b - above and west of the nucleus of maximum salinity at A19a.

On the northern section, temperature is associated with depth rather than with salinity, the isotherms crossing the isohalines without interruption. Thus the water of maximum salinity (35.32°/oo) at C21d becomes cooler with increasing depth while the fresher water in the upper layers at A21a and B21a is as warm as the salter water on both sides of it. The 8°C, isotherm is only very partially linked to the 35.25°/oo isohaline, whereas in spring this association was generally found to be more or less complete.

On the southern section, while temperature also increases from the surface downwards and the fresher surface water at A19d gives no inflection to the isotherms, the maximum salinity water in the lower layers at A19a is uniformly 9°-10°C. and the 8°C. and 35.25°/oo iso-:pleths are for the most part closely linked.

Normal/

Normal relations of temperature to salinity thus obtain in the lower layers and scarcely at all in the upper. In the upper layers, moreover, temperature is higher than in spring of the previous years. It would appear that these high temperatures are largely due to the greater summer insolation and are not borne to the region by the Atlantic stream as in spring. The amount of warming from solar radiation is, for practical purposes, identical in salter and fresher waters, a fact which explains the absence of correlation between isotherms and isohalines in the upper layers in July 1913.

The fresher water on the south-east flank of the southern section has already been noted to resemble in temperature the Atlantic water at similar levels. At the station nearest to Faroe on each section, however, temperature is more uniform from surface to bottom. Mixing is doubtless the reason for the reduction of the thermal gradient.

The temperature of the bottom Norwegian Sea water in the depths of the Channel is characteristic, in like case to its salinity, zero and negative temperatures being recorded. On both sections the $35.00^{o}/oo$ isohaline is associated with the isotherms of $4-5^{o}C$. For the northern section this is similar to, and for the southern rather warmer than is generally found to be the case in spring.

The same material as forms the vertical sections, with, in addition, one station on the east side of Faroe, is used in the construction of the horizontal charts HC(13)1-5.

Unlike the charts for the Faroe-Shetland Channel in the two previous years, the HC(13)1-5 do not all show the Atlantic stream as a

SW/

S.W. → N.E. axis of high salinities on the S.E. side of the Channel. The axis is well defined at 50 and 100 metres (HC(13)3 and 4) but on the remaining three planes it is obscured by the circumstance that the nucleus of maximum salinities is deeper in the south than in the north. At 50, 100 and 200 metres, fresher and colder water extends southwards in the centre of the Channel, again providing, as in May 1911 and in May/June 1912 an element which, in conjunction with the contrary-moving Atlantic stream, will tend to set up eddy-motion.

The T-S diagram, TS(13)1 comprises the same data as do the horizontal charts and allows of a final summing-up of hydrographic conditions in the Faroe-Shetland Channel in July 1913.

Apart from the higher surface temperatures due to its pertaining to the month of July, TS(13)1 is akin to the T-S diagrams for the Faroe-Shetland Channel in spring of the two previous years. The same elements as were present in TS(11)1 and TS(12)1 make up TS(13)1, namely (a) a concentration of depth marks representing Atlantic water. The salinity, 35.20°/oo - 35.30°/oo, and the lower temperature limit, 8°C., are similar to those of this type in 1911 and 1912. The individuality of TS(13)1 lies in the great prolongation upwards of the (a) grouping owing to the high surface temperatures consequent on the season - July. (b) A second cluster of depth marks and parts of curves with 34.92°/oo salinity and temperatures from -1°C. to 3°C. These limits are identical with those in spring in 1911 and 1912 and define the bottom Norwegian Sea water-type as found in the Channel. (c) The oblique line joining the bottom of (a) to the upper surface of (c). This, as before, is the line of mixing between the two major water-types.

So far, the higher surface temperatures are the only point of difference/

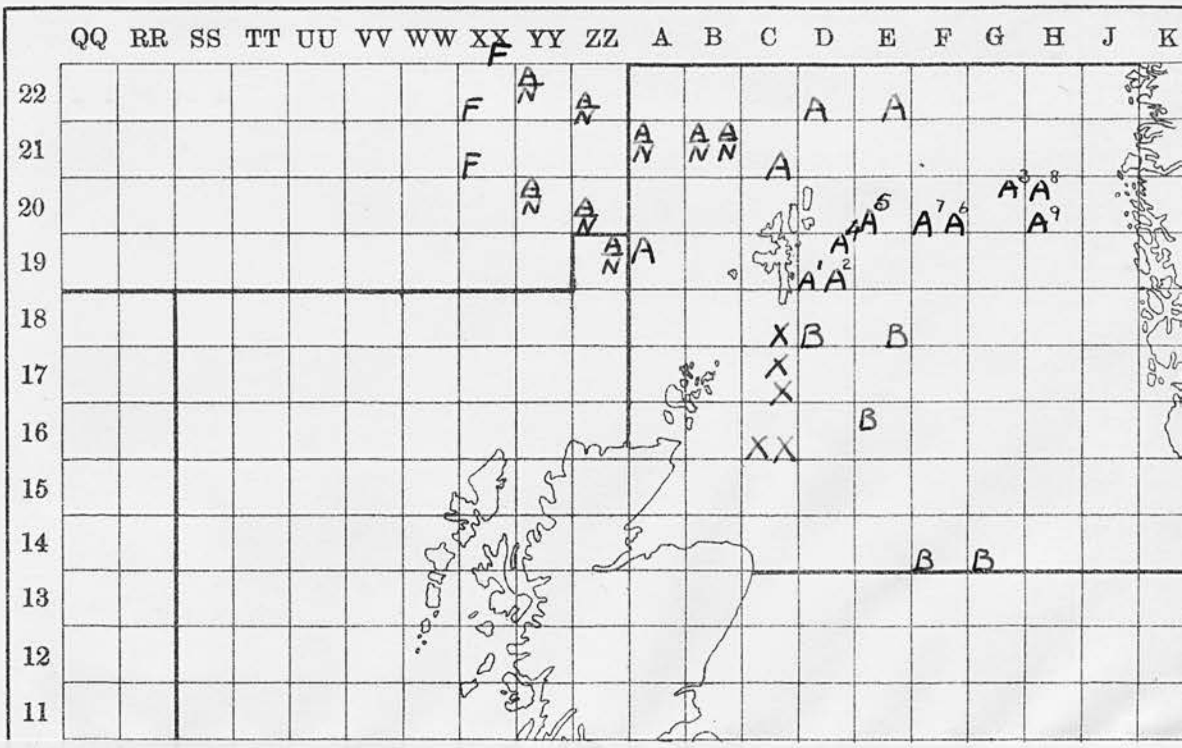


Figure 16.

Distribution of Water-Types, June/July 1913.

Salinity and temperature of the water-types shown on Figure 16, together with the positions and dates of the stations whose T-S curves made up the groupings which represent the above types.

A
(35.20-.30°/oo x 8°C)(bottom)

TS(13)1

10	A19a	13/7
15	C21d	16/7

TS(13)2

2	D22c	17/7
3	E22d	17/7

$\frac{A}{N}$

TS(13)1

4	YY22a	10/7
5	YY20a	12/7
6	ZZ22c	10/7
7	ZZ20c	12/7
8	ZZ19b	13/7
9	A21a	10/7
12	B21a	9/7
13	B21b	9/7

F
(35.15-.20°/oo x 8-10°C)

TS(13)1

1	XX23d	10/7
2	XX22c	11/7
3	XX21c	12/7

A'
(35.20-.30°/oo x 6-8°C)(bottom)

TS(13)4

A^1	17	D19c	6/7
A^2	18	D19d	25/7
A^3	30	G20b	19/7
A^4	16	D19b	20/7
A^5	23	E20c	20/7
A^6	28	F20d	19/7
A^7	27	F20c	19/7
A^8	32	H20a	19/7
A^9	33	H20c	19/7

X
(35.05-.20°/oo x 8-9°C)

TS(13)4a

1	C18d	22/6
2	C18d	6/7
3	C17b	22/6
4	C17b	6/7
5	C17d	22/6
6	C17d	5/7
7	C17d	30/7
8	C16c	22/6
9	C16c	5/7
10	C16d	30/7

B
(35.00-.10°/oo x 6.5°C)

TS(13)4

19	D18c	6/7
24	E18d	25/7
25	E16a	25/7
29	F14c	17/7
31	G14c	16/6

difference between 1913 and 1911/1912: another dissimilarity, however, exists. In 1911, the T-S curves representing water on the Faroe Shelf lay entirely on the line of mixing (c) and in 1912, partly so. In 1913, however, curves 1, 2 and 3 (for the stations nearest Faroe) stand distinctly apart from the line of mixing. The salinity of this Faroe type is similar to that in 1911 and 1912, higher temperature being the factor which differentiates this water from that in the same locality in 1911 and 1912. In 1913, therefore, this Faroe water is not a product of mixing between the bottom Channel water and the Atlantic stream as found in July. The explanation suggested for the slightly higher temperatures off Faroe in May-June 1912 than in May 1911, namely, greater insolation with approach of summer, may apply in the case of July 1913, but on the other hand this Faroe water may not be a simple mixture-type but a complex, to whose origin the T-S diagram gives no clue.

The distribution of water-types in the Channel is shown on Figure 16.

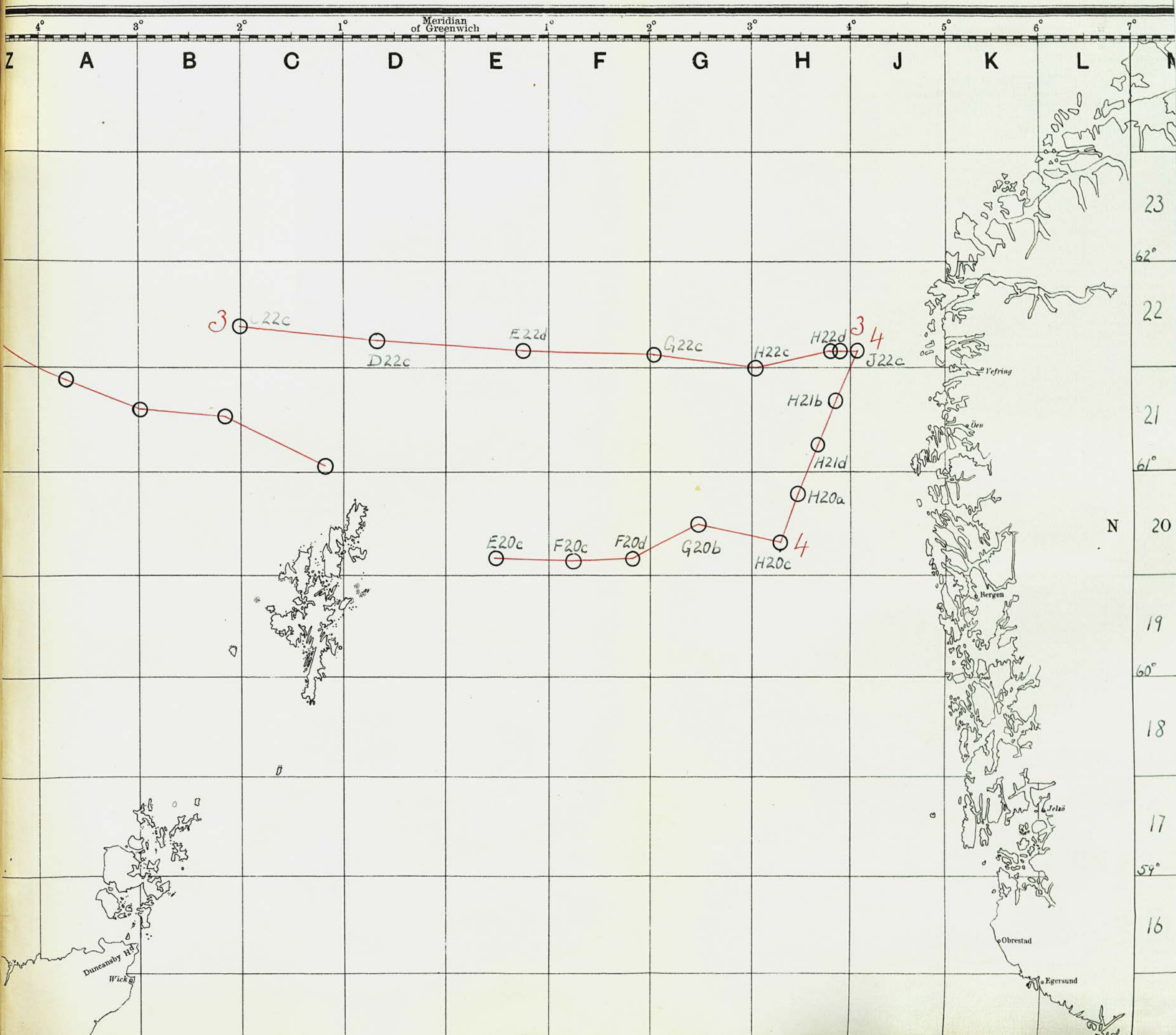
Broadly, the hydrography of the Faroe-Shetland Channel in July 1913 is characterised by relative scarcity, as in 1912, of Atlantic water, the stream, however, being broader and shallower than in that year. Surface temperatures are higher than in spring of former years, but in the deeper layers thermal conditions remain unchanged.

FIGURE 17.

FIGURE 17.

POSITIONS OF SECTIONS.

SOUTHERN NORWEGIAN SEA, 1913.



SOUTHERN NORWEGIAN SEA.

Hydrographic observations were made on the 17th and 18th of July at the usual stations extending in a straight line across the Southern Norwegian Sea. No supplementary foreign material is available as in 1911 and 1912, but additional and contemporaneous Scottish stations stretch from the east end of the usual line southwards and westwards to Shetland, as shown on Figure 17 on which, also, the section-numbers are given. On account of the crowding of the isopleths, the eastern portion of VS(13)3 has been re-drawn with the vertical scale enlarged from 1 : 5,000 to 1 : 2,000. The standard horizontal scale is adhered to. The horizontal charts HC(13)1-5 illustrate also the more or less contemporaneous conditions in the Faroe-Shetland Channel and Northern North Sea. Only the Southern Norwegian Sea data from stations north of latitude 61°N. appear on the T-S diagram TS(13)2.

The Atlantic water on the Southern Norwegian Sea section VS(13)3 lies, as in spring generally, on the stretch of Continental Shelf between D22c and E22d and occupies a cross-sectional area of 33Km^2 as outlined by the isohaline of 35.25°/oo. This is a smaller area than is found in spring in 1911 or 1912 and indeed less than that generally found in spring from 1902-1912. It is greater, however, than the area of Atlantic water on the northern Faroe-Shetland Channel section (18Km$^{2)}$. in July 1913, though less than that on the southern section (38Km^2). In this respect also, conditions in this region in July 1913 differ from those in spring in 1911 and 1912, for in the two latter instances the cross-sectional area of Atlantic water in the Southern Norwegian Sea exceeded that on either of the Faroe-Shetland Channel sections at the same season. Atlantic influence in the Southern Norwegian Sea in July 1913 would therefore seem to be less even than in spring 1912.

Salinity/

Salinity in the Atlantic stream on VS(13)3 reaches a maximum of $35.37^{\circ}/oo$ on the surface at D22c. This maximum and the position of its occurrence is identical with that in May/June 1912, the salinity reached being one exceeded only once in the series of spring months from 1902-1910. It is also higher than the maximum on both Faroe-Shetland Channel sections in July 1913. Thus it appears that the Atlantic water in the Southern Norwegian Sea in July 1913, though below normal volume, is more than usually concentrated.

A few miles westwards of D22c the Atlantic stream is bounded by fresher water, the maximum salinity at C22c being only $35.19^{\circ}/oo$. In spring of 1911 and 1912 there was Atlantic water in the upper levels at this station. Eastwards the Atlantic stream reaches G22c, the same position as it attained in 1912 but 29 miles west of the limit in 1911.

Unlike 1911 and 1912, the maximum temperature on VS(13)3 of $13.22^{\circ}C.$ is not found in the Atlantic water but at the surface of the eastmost station J22c. The temperature of the $35.37^{\circ}/oo$ water at D22c is $12.30^{\circ}C.$ - higher than in 1912. As a whole, also, the Atlantic water is warmer than in spring of former years, but though the temperature of the upper 80 metres exceeds $9^{\circ}C.$ in the lower layers thermal conditions resemble those of spring 1911 and 1912, temperature being $8^{\circ}-9^{\circ}C.$

In the deep water west of the Atlantic stream, salinity falls at 300 m. on C22c to $34.92^{\circ}/oo$ and temperature to $3^{\circ}C.$ This is the upper surface of the bottom Norwegian Sea water, which, with increasing depth, varies very slightly in salinity while temperature diminishes to $-0.97^{\circ}C.$ The freshening influence of this water-type can be seen even at the surface of C22c.

On the east side also, the Atlantic water is bounded by low salinities. In/

In the upper layers these reach a minimum of 31.20°/oo at J22c while the freshening influence spreads almost to D22c, considerably further than in 1911 and 1912. Station E22d, which was often the seat of maximum salinity in spring, has a surface salinity of only 34.47°/oo. The great spread of fresh water outwards from the Norwegian coast is doubtless due to the summer increase in the Baltic outflow, and possibly also to the lower resistance offered by the comparatively weak Atlantic stream at this season. Most of the Baltic water is below 7°C. in temperature, there being a steep temperature gradient from almost 12°C. on the surface to less than 8°C. at 20 m.

Underneath the Baltic water, modified Atlantic water spreads east from G22c in a lobe of higher salinities to the bottom at H22d (3°50'E.). In the deep trench below this, however, salinity and temperature fall away again to 34.07°/oo and 5.34°C. The hydrographic conditions under the unusually fresh Baltic water are thus similar to those found in spring 1911 and 1912.

Conditions off the Norwegian coast are further illustrated by VS(13)4. On account of the short distances between stations and the closeness, vertically, of the observations in the upper layers, the horizontal scale has been doubled and the North Sea vertical scale employed. A skeleton section on the standard horizontal scale is also given.

Salinity exceeds 35.25°/oo in the lower 200 m. at H20c and is over 35.20°/oo in a belt north from this in intermediate layers to H21b. The upper layers are occupied by fresh Baltic water which also floods all depths at J22c. Underneath the salter water salinity diminishes to 35.08°/oo at the bottom of H21d.

Temperatures in the upper 25 m. exceed 8°C. and rise to over 12°C. on the surface. In the underlying layers, the axis of

higher/

higher salinities is for the most part between 7°C. and 8°C., while the deep Baltic water at J22c is less than 7°C. From 50-150 m. at H21d there is also a body of less than 7°C. water, doubtless related to that of the same temperature in the extreme north. At the bottom of H21d temperature is only 5.26°C., in association with the low salinity at the same position. This low salinity is separated by one of $35.16^{\circ}/oo$ at the bottom of H21b from the fresh Baltic water, indicating that the temperature of less than 6°C. has no connection with the low temperature of the deep Baltic water, but is a distinct entity, related, as will be seen later, to the bottom Norwegian Sea water.

VS(11)4 has thus the same elements in its constitution as the east end of the Southern Norwegian Sea section VS(13)3, though these two lines of stations are at an angle of about 60° to each other. A current connection is suggested and this relationship may best be investigated with the aid of the horizontal charts.

On the surface, as shown on HC(13)1 the remarkable spread of Bal-:tic water west to the prime meridian masks the essential features in the Southern Norwegian Sea at this time. At 20 metres the screen of fresh water still covers the area west to longitude 1°E., but at 50 m. the underlying distribution of salinity and temperature appears. On HC(13)3 and 4 (50 and 100 metres) the axis of highest salinity water ($35.30^{\circ}/oo$) holds on north-eastwards from the Faroe-Shetland Channel and evinces no tendency to turn into the North Sea, as, on the other hand, the over -$35.25^{\circ}/oo$ water does. The Atlantic water as limited by the latter isohaline passes southwards across lat. 61° N. in two places, the greater proportion being on the east side of Shetland and the remainder reaching almost to the Viking Bank. Between these two lobes of Atlantic water, however, lower salinities/

salinities and temperatures push north along $1^{O}E.$, this tendency being more pronounced at 50 than at 100 metres. In 1911 and 1912 the Atlantic water crossed the Southern Norwegian Sea to about $2^{O}E.$, thereafter, in the case of 1911, doubling back to the east side of Shetland, while in 1912 it passed directly southwards into the east side of the Northern North Sea. In 1913, however, the spur of fresher colder water along longitude $1^{O}E.$ appears to have split the Atlantic stream, the minor part being found in the neighbourhood of the Viking Bank while the main body turns directly round the north of Shetland. The position of the axis of over -$10^{O}C.$ water on HC(13)3 shows, however, that there is a tendency for the Atlantic water to approach the east side of Shetland from the east of north.

The data for the Southern Norwegian Sea may now be examined from a different angle, utilising TS(13)2.

In its general aspect, this diagram differs from those for the same region in spring 1911 and 1912 in having its curves more dispersed and in several instances a remarkable extension to low salinities. Though the water-types in the Southern Norwegian Sea are not so boldly indicated on TS(13)2 as formerly, they can, however, still be distinguished. The Atlantic type is represented by the bottoms of curves 2 and 3, the bottom Norwegian Sea type by the lower third of curve 1 and the line of mixing is traced by the bottoms of curves 4, 8 and 9.

The loosely-grouped character of the curves on TS(13)2 is mainly due to the relative poverty of Atlantic water and abundance of Baltic water. This relationship may therefore be regarded as the character-:istic feature of the hydrography of the Southern Norwegian Sea in July 1913.

Further detail can be derived from an examination of the individual/

individual curves. Curve No. 1 in its lower part is typical of bottom Norwegian Sea conditions but its upper part bears no relation to major water-types. The upper water-layers of the station represented, C22c, are doubtless composed of Norwegian Sea water, the temperature of which has been raised mainly by direct insolation.

Curve 2 and the bottom of Curve 3 represent the Atlantic type, while the upper part of the latter is diverted to the left by the presence of Baltic water.

Curve 4 also has low surface salinity and moves towards the co-ordinates of the Atlantic type, but before these are reached the influence of bottom Norwegian Sea water predominates and the lower part of curve 4 lies on the Atlantic - bottom Norwegian Sea (A-N) line of mixing,

The upper parts of curves 5, 6, 7 and 10 originate at various degrees of low salinity and then follow a common path more or less straight towards the A-N line. Before this is reached, however, and just prior to developing a density of 27.5, the curves (except No.10, which terminates here) undergo a sharp flexure and in company with curve 9 pursue a course sub-parallel to the isopicnal of 27.5 between temperatures of 6° and 7°C., indicating that A water is now particip-:ating in the composition of the curves. (It is to be observed that the density of the A water is also slightly less than 27.5, which would seem to be a critical value, having attained which the water repre-:sented by curves 5, 6, 7 and 9 is enabled to mix with the Atlantic type). With increasing density, however, the curves again indicate a change in the proportion of the ingredients of the mixture. Curve 5 becomes inexplicably erratic, curve 7 reaches bottom, and in curves 6 and 9 the bottom Norwegian Sea water element becomes dominant.

Curves 8 and 9 resemble 5, 6, 7 and 10 in their upper parts, but first/

first No. 9 and then No. 8 swings off under Atlantic influence. Curve 8 almost attains Atlantic salinity and temperature but is finally dominated by the bottom Norwegian Sea type as, in the manner noted above, is Curve 9, both passing on to the A-N axis.

From the above, it is clear that the Southern Norwegian Sea is the meeting-place of at least three main types of water, which undergo complicated mixing processes in the area. At the same time it is obvious that the Atlantic water entering the North Sea via the Southern Norwegian Sea is liable to modification from two principal sources, the bottom Norwegian Sea water and the Baltic water. The former is probably the more constant factor, since it operates in the comparative seclusion of great depth, mixing with the under-side of the Atlantic water. The Baltic water is more periodic in its effect, swelling to a maximum volume in summer and dwindling in winter.

In July 1913 the Southern Norwegian Sea is characterised by a paucity of Atlantic water, doubtless the reason for the greater prominence of the complicating factors than in the spring of 1911 and 1912.

FIGURE 18.

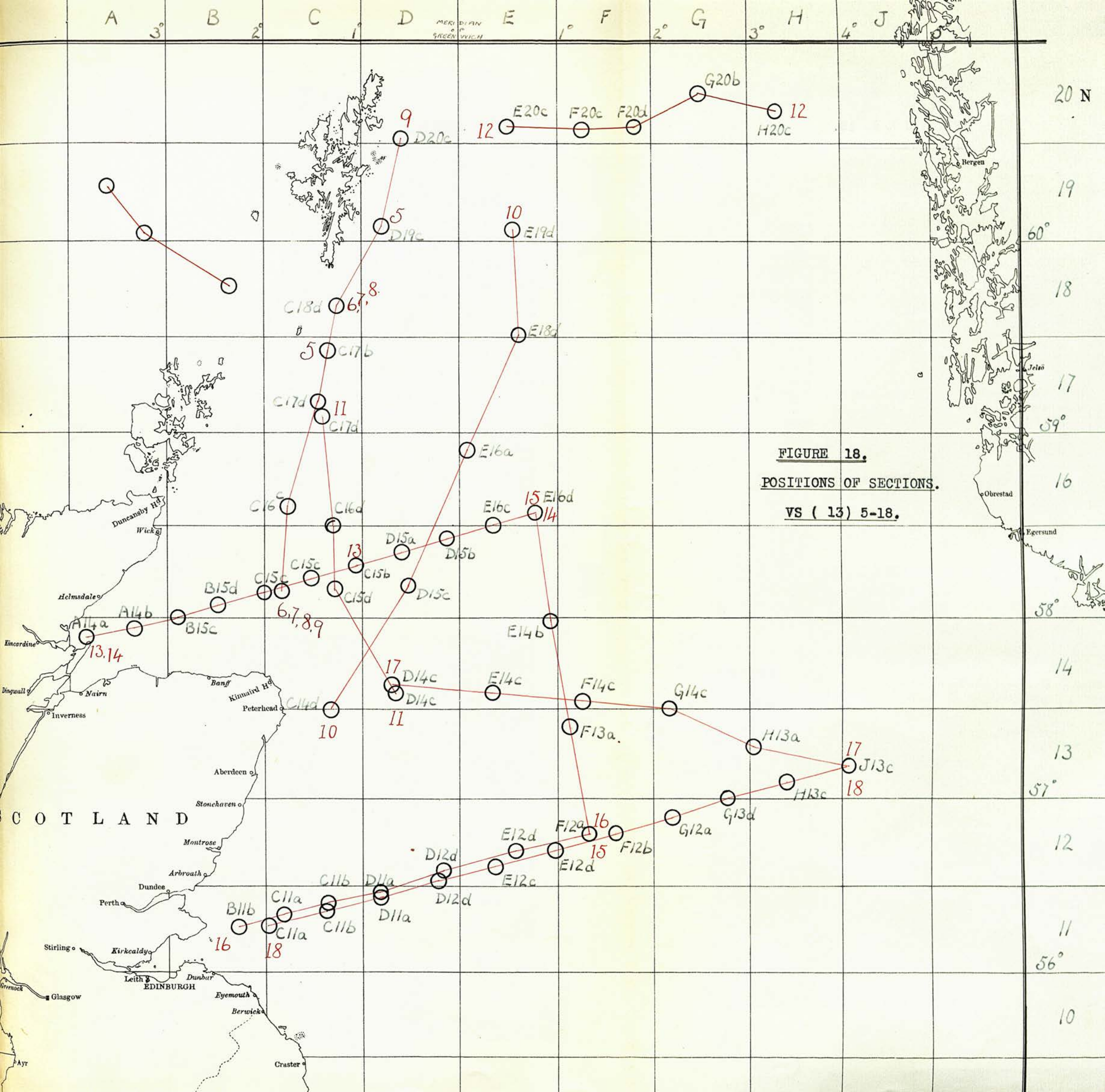


FIGURE 18.

POSITIONS OF SECTIONS.

VS (13) 5-18.

NORTHERN NORTH SEA.

Data are more plentiful for the Northern North Sea than in 1912, but are confined to the western part of the area, as shown by Figure 18, on which the positions and numbers of the sections are given. The Aberdeen-Shetland line was traversed in April, May, June and July and partially also in March. These five sections VS(13)5-9 are plotted on the same sheet, with stations common to all in the same vertical line.

March. VS(13)5 illustrates the vertical uniformity of salinity and temperature occasioned by convection currents in winter. Salinity and temperature are highest, reaching 35.28°/oo and 7.30°C. opposite Fair Isle, at the bottom of C17b. At C18d salinity is lower, but rises again at the northmost station D19c.

The salter water at C17b is of Atlantic type, and its position might suggest that Atlantic water was moving from west of Fair Isle. Station C18d, however, opposite the Fair Isle-Shetland gap, has the lowest salinity on VS(13)5, indicating that if water is entering the North Sea by this Channel it is of north-west Scottish coast and not Atlantic origin.

April. VS(13)6 has lower salinities at C17b than in March, temperature also being slightly less, while C18d is still relatively fresher than C17b, southwards of which salinity again diminishes.

The Atlantic water present in March seems to have been diluted away, possibly by north-west coast water, as the lower salinities at C18d in both March and April would suggest. The presence of higher salinities off Fair Isle than immediately to the north argues either that the salter water reached this position from the east of north or simply that a former Atlantic influx is being attacked by fresher water from south of Sumburgh, leaving an isolated block of higher

salinities/

salinities off the east of Fair Isle.

An alternative source from which salinity may be reduced between March and April is indicated by the bending north of the isohalines in their upper parts in the southern half of the section, suggesting a movement of fresher water northwards from the Moray Firth region as in 1911.

<u>May.</u> By May (VS(13)7) salinity has decreased still further, only the bottom layers exceeding 35.00°/oo. The bulge northwards of the isohalines in the upper layers in the south is more marked than in April, suggesting to a greater extent than formerly that the freshening influence is from this quarter.

Surface temperatures now exceed 8°C. and the 7°C. isotherm encloses a smaller area.

<u>June.</u> The level of salinity rallies somewhat in June (VS(13)8) the 35.10°/oo isohaline reaching further south, though only in the bottom layers, than in April. There is still indication, however, of a north-going stream of fresher water on the surface and the presence of north-west coast water may be suspected at C18d where the surface salinity is relatively low.

Temperature has risen considerably since spring, 2°C. at the bottom and 3°C. in the surface layers. The isohalines and isotherms crowd together between depths of 10 and 30 metres south of C17d, that is, there is something of a plane of discontinuity at this level. C18d shows little range of temperature between surface and bottom.

<u>July.</u> Salinity further increases in July (VS(13)9) the 35.20°/oo isohaline appearing south of C18d, and the 35.10°/oo line, though still attaining only C16c, rises somewhat to include a greater cross-sectional area. The maximum salinity is in the surface at the extreme north,/

north, where 35.30 $^{\circ}/oo$ is reached. In the extreme south, however, at C15c, salinity is lower than in June. It appears probable, nevertheless, that something in the nature of an Atlantic influx, though feeble, is depicted on VS(13)9, the first since that prior to March.

Temperature also has risen since June, the surface now for the most part being warmer than 11°C. and the amount of less than 9°C. water in the lower levels is diminished.

A marked break in the trend of the isotherms occurs at C18d, which has a range from surface to bottom of only .48°C. Since March, C18d has had a lower range of temperature than its neighbour C17b. Station C18d is opposite the Fair Isle-Shetland passage, where tidal mixing doubtless smoothes out temperature variation.

There are three further sections in the Northern North Sea in July.

VS(13)10 is roughly parallel to the Kinnaird Head-Shetland line of VS(13)5-9 and some 50 miles east of it. It is almost three weeks later in date than VS(13)9.

The most prominent feature of VS(13)10 is the steep thermal gradient between 25 and 50 metres, in which temperature falls from over 12°C. to less than 8°C. This condition is fully developed only north of D15c. Below the temperature gradient and north of D15c salinity varies only slowly. Above it a rapid decrease takes place into much fresher water, doubtless of Baltic and Continental origin. There is thus a plane of discontinuity at about 30 metres. The presence of this plane and the uniformity of salinity below it, with temperatures less than 7°C. at the bottom, argues that the water here is in very slow circulation.

South of D15c the surface is cooler and the bottom warmer than to the north, while the isohalines are vertical and fairly close - clearly/

clearly a distinct hydrographic region from that north of D15c.

A third July section, VS(13)11, stretches from off Peterhead towards Fair Isle, crossing the south end of VS(13)10 and running more or less parallel to VS(13)9.

The maximum salinity is in the north, at C17d, where it is only slightly less than at the station worked in the same sub-rectangular area 25 days before (VS(13)9). Southwards salinity decreases gradually. The temperature range is high, from over 12°C. to under 8°C., but the gradient is not so steep as to constitute a plane of discontinuity. The more or less stagnant water which was shown on VS(13)10 does not appear.

The one remaining section for July, VS(13)12, lies between Shetland and Norway. Water of Atlantic type, that is, with salinity in excess of 35.25°/oo, occurs in the lower layers in the west at E20c and at G20b and H20c, where it floods the deep trench. The water between these two high salinity masses is mostly over 35.20°/oo. In the upper layers, however, very low salinities are recorded, the Baltic water spreading west in the upper 20 metres almost to E20c.

Temperature conditions support the division of the section into the regions noted above. Highest temperatures occur in the upper, fresher layers and the two bodies of high salinity water are between 7° and 8°C., while much of the bottom water at F20c and F20d is cooler than 7°C. This central cold bottom water separating the two masses of modified Atlantic water is doubtless related to that of similar temperature but somewhat higher salinity on VS(13)10. Conditions on VS(13)12 are thus analagous to those on the similar line of stations in 1911.

The/

The two sections from stations in and eastwards of the Moray Firth may now be examined.

VS(13)13 depicts conditions in April. Salinity is everywhere low, reaching 35.00 $^{o}/oo$ only on the surface in the east and falling below 34.00 $^{o}/oo$ in the west. Between A14a and B15c, salinity increases steadily eastwards, but between B15c and C15c the rate of increase diminishes very much, to rise again east of C15c. Eddy motion between B15c and C15c may be the reason for the uniformity of salinity there.

Temperature follows a course broadly similar to that of salinity, being highest in the east and lowest in the west.

Three weeks later, the same line of stations was pushed further east. Salinity on VS(13)14 is slightly greater than on VS(13)13 and temperature also is higher by from .5 to 1°C. A line from the surface of C15b to the bottom at C15c (2°W.) divides the section into two hydrographic regions. Westwards salinity falls off slowly, but eastwards the water is all at about 35.00 $^{o}/oo$, the upper layers being rather less and the lower layers rather more than this value. The uniformity in the east may be the foundation of the similar condition in July, as shown on VS(13)10.

The 7°C. isotherm does not support the above partition of the section, being deepest at C15b and rising slowly to the surface on either side of this station.

Hydrographic conditions in July 1913 are alternatively depicted on the horizontal charts HC(13)1-4 which must, however, be used with caution, as the Aberdeen-Shetland line of stations was worked two weeks before the parallel line further east.

The chief feature at the surface (HC(13)1) is the Baltic water, which/

which spreads west over the area, the $35.00^{o}/oo$ isohaline approaching to within 40-50 miles of Shetland and passing even further west south of this. From the Moray Firth, Scottish coast water spreads out eastwards, almost meeting the Baltic water, but leaving a narrow lane of over $35.00^{o}/oo$ water as the prolongation of the axis of high salinities southwards from Shetland.

Atlantic water appears only on the north-east of Shetland and in a modified form on the south-east and south of these islands.

Temperature diminishes from east to west, but part of this gradient may be due to the time-factor noted above.

Conditions at 20 metres resemble those on the surface, except that the Baltic water does not attain quite such a westerly spread, particularly in the north.

At 50 metres (HC(13)3) Baltic water is entirely absent and the Atlantic water is now clearly visible. The southern limit of high salinities is still just south of Shetland, but the width of this water is greater than at 20 metres.

The thermal gradient is in the opposite direction to that in the upper layers, being now downwards from west to east, that is, the western part of the area has a smaller range of temperature than the centre. More oceanic conditions, brought by Atlantic influence, are indicated in the west, while the water in the centre seems to be relatively motionless (as was argued from the sections), allowing insolation to raise temperatures in the upper layers.

On the deepest plane, 100 metres, represented on HC(13)4, the $35.20^{o}/oo$ and $35.10^{o}/oo$ isohalines are still at the same latitude as in the layers above and temperature also is higher in the west than in the centre. A wedge of less than $35.10^{o}/oo$ and $7^{o}C.$ water pro-:jects from the centre of the area to D18c in a manner analagous to that of the larger wedge of central water in August 1911.

The/

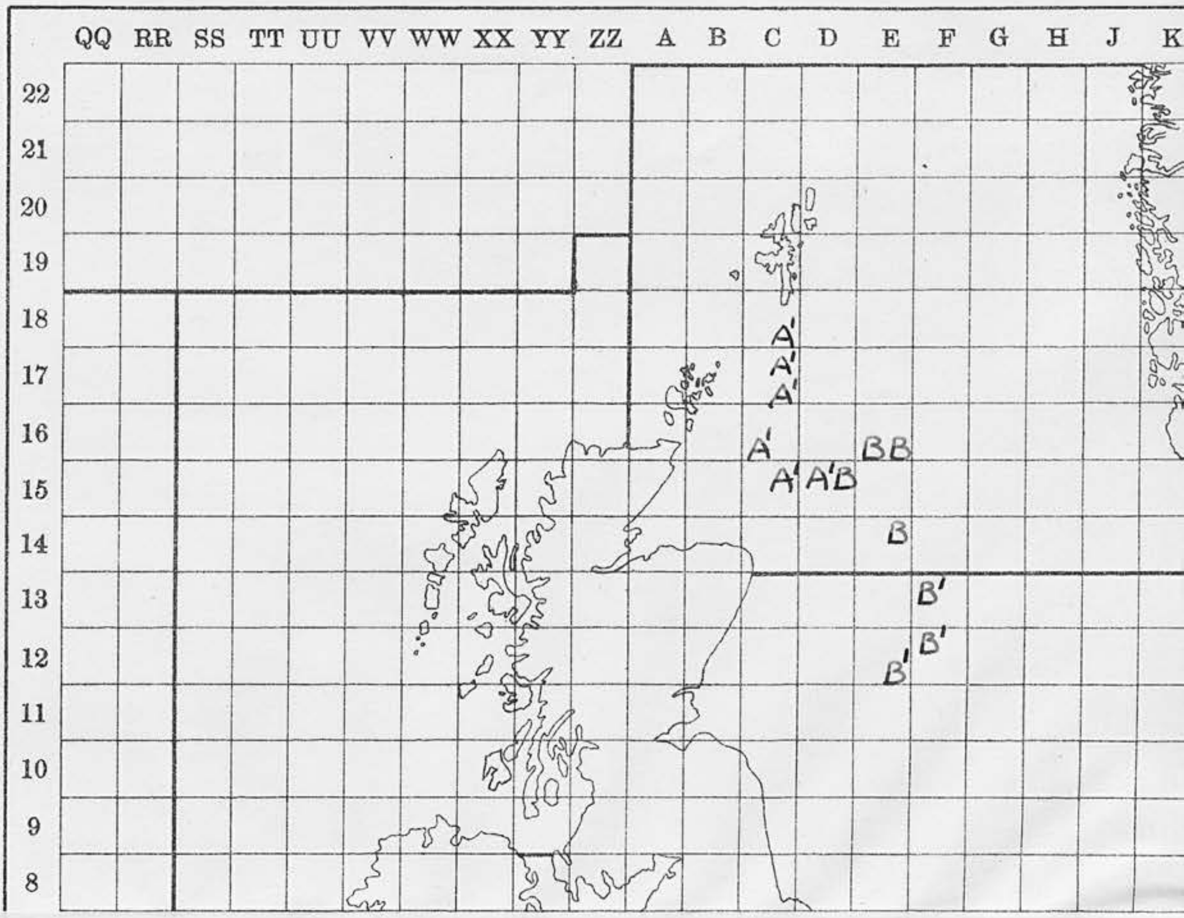


Figure 19.

Distribution of Water-Types in April and May 1913.

Salinity and temperature of the water-types shown on Figure 19, together with the positions and dates of the stations whose T-S curves make up the groupings which represent the above types.

A'

($35.00\,{}^{0}/_{00}$ x 6.5–$7.25^{\circ}C$)

TS(13)3a

10	C18d	14/5
13	C17b	13/5
15	C17d	13/5
16	C16c	24/4
17	C16c	13/5
18	C15b	8/4
19	C15b	30/4
26	D15a	30/4

B

($35.00\,{}^{0}/_{00}$ x 6–$6.5^{\circ}C$)

TS(13)3

27	D15b	30/4
28	E16c	30/4
29	E16d	30/4
30	E14b	1/5

B'

(34.90–$35.00\,{}^{0}/_{00}$ x 5.75–$6^{\circ}C$)

TS(13)5

29	E12d	1/5
31	F13a	1/5
32	F12a	1/5

The T-S curves for stations worked in the Northern North Sea in March, April and May are plotted on TS(13)3 and 3a. Use is made of a transparency in the interests of clarity.

The curves chosen for the transparency form a series whose bottoms constitute a water-type, of salinity 35.00°/oo and temperature 6.5°-7.25°C. The group includes stations worked in April and May, so little did conditions change over the period. Though this type falls short of the salinity of the Atlantic water in the area in the same season of 1911, it is styled "A′" on Figure 19, since it is the nearest representative of the Atlantic type in spring 1913. On Figure 19, too, it lies over the area occupied in 1911 by the Atlantic influx to the North Sea. The disparity between the salin-:ity of this A′ type in the North Sea in spring 1911 and spring 1913 is an index of the poverty of Atlantic influx to the area in the latter season.

A second bottom type may be distinguished on TS(13)3, where four curves run to bottom with salinity of 35.00°/oo and temperatures 6°-6.5°C. This type differs from the first only in having temperature 1°C.lower, but as temperature varies little in spring, a difference of 1°C. is quite significant.

On Figure 19 the four curves with bottoms of this type, indicated by the letter B, lie in the centre of the Northern North Sea.

The March curves, 4, 8, 11 and 25, for stations off Shetland, do not group themselves, and the remainder of the curves represent stations near the Scottish coast, mainly in the Moray Firth.

June and July hydrographic observations in the Northern North Sea are incorporated in TS(13)4 and 4a, a transparency again being utilised to obviate overcrowding.

The saltest and most definite concentration of points is the elongated, oblique one on TS(13)4, between salinities of 35.20°/oo and/

and 35.30^{0}/oo and temperatures of 6.5^{0}C. and 8^{0}C. All the curves involved run to bottom in this group, that is, it represents a bottom water-type. The upper parts of the curves are quite diverse. The group comprises only July station-curves. The salinity limits indicate Atlantic derivation but the temperatures are low compared with those of the Atlantic influx in the summer of 1911. The group may, however, be plotted as A$'$ on Figure 16 where it occupies the north of the area.

Referring back to the T-S diagram for the Southern Norwegian Sea, TS(13)2, and plotting the co-ordinates of the above A$'$ type on it, the reason for the low temperatures of the type becomes apparent - bottom Norwegian Sea water enters into its composition, as shown by the circumstance that the A$'$ group falls on the line of mixing. The oblique elongation, noted at the outset, of the group is due to the varying proportions of colder fresher water in the mixture. Indices 1,2,3..... may therefore be added to the "A$'$"s on Figure 16 to represent increasing proportion of bottom Norwegian Sea dilution of the Atlantic water.

Another concentration of depth-marks, smaller and less closely knit than the A$'$ type, is formed by the bottoms of one June and four July curves on TS(13)4. Salinity is 35.00^{0}/oo to 35.10^{0}/oo and temperature 6.5^{0}C. This type appears on Figure 16 in the centre of the area, hence its designation, B, since it differs only slightly from the type of the same name in spring. The hydrographic condit-:ions of the central area have thus changed little in the lower layers from spring into summer.

The curves on TS(13)4a are clearly of another character from those on TS(13)4, having, on the whole, lower salinities and higher bottom temperatures. As in TS(13)4, an obliquely elongated group is formed by bottoms of curves, the salinity limits being 35.05^{0}/oo and 35.20^{0}/oo and temperature 8^{0}C and 9^{0}C. This group is one which

has/

has not previously (1911-1913) been recorded in the North Sea and its position on the T-S diagram shows that it is not directly derived from the major water-types. The occurrence of the type is therefore indicated by X on Figure 16. The long axis of the concentration of depth-marks is, however, roughly parallel to that of the group on TS(13)4. It is possible therefore that the X group fell originally on the same line of mixing as the A′ group, but that it has lain in the north-western area of the North Sea long enough for temperatures to be raised by solar warming. Doubtless Scottish coastal water reduced salinities at the same time. This view is supported by the fact that this water-type persisted at most of the stations where it is found from June to July. (See table to Figure 16). If these suppositions be true, then there is further ground for believing that Atlantic influence was feeble in the Northern North Sea in the earlier half of 1913.

Curves 32 and 33 are like and pursue the same devious courses, due to complicated mixing, as the curves for this north-eastern area which were discussed at some length in connection with TS(13)2.

MIDDLE NORTH SEA.

Suitable lines of stations for sections in the Middle North Sea are available only in May and June. The positions of these sections are shown on Figure 18. The data for the remainder of the stations visited, however, appear on the T-S diagrams.

May. The first of the two May sections to be considered, VS(13)15, is meridional at about longitude 1°E.

Broadly, salinity is characterised by an increase in all directions from a minimum of less than $34.80^{\circ}/oo$ on the surface at E14b and surpasses $35.00^{\circ}/oo$ only in the lower layers in the north. The isotherms also are more or less symmetrical about E14b, temperature being below $6^{\circ}C.$ at the bottom north and south.

The upper layers at E14b are thus apparently derived from a different source from the remainder of the water on the section. The origin doubtless is Continental or Scottish coastal water.

The other May section is VS(13)16, continuing the south end of VS(13)15 to the Firth of Forth.

Salinity is highest in the east and falls off more or less uniformly westwards. The flexures of the isohalines indicate that fresher water is moving out in the upper layers from the Scottish coast. Temperature increases equally uniformly from less than $6^{\circ}C.$ on the bottom to over $7^{\circ}C.$ at the surface.

June. VS(13)17 runs from Kinnaird Head to Fisher Bank.

Salinity exceeds $35.00^{\circ}/oo$ only in the bottom layers of G14c and at the surface of J13c. In the upper layers at E14c and F14c, salinity is at a minimum of less than $34.70^{\circ}/oo$ and increases outwards in all directions. This fresher surface water is in the same/

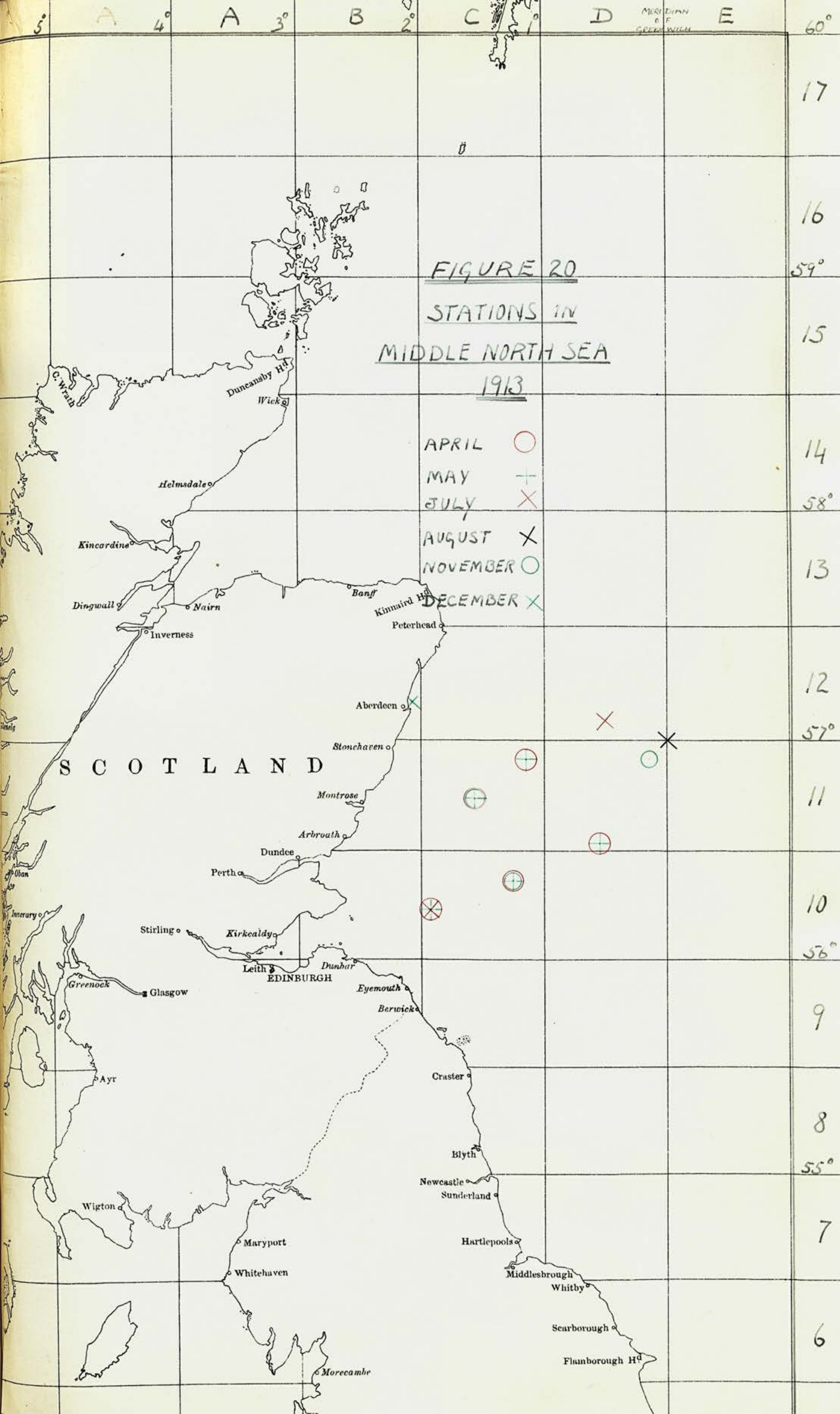


FIGURE 20
STATIONS IN
MIDDLE NORTH SEA
1913
APRIL
MAY
JULY
AUGUST
NOVEMBER
DECEMBER
MERIDIAN OF GREENWICH
A
B
C
D
E
5°
4°
3°
2°
1°
60°
59°
58°
57°
56°
55°
17
16
15
14
13
12
11
10
9
8
7
6
SCOTLAND
C. Wrath
Duncansby Hd
Wick
Helmsdale
Kincardine
Dingwall
Nairn
Inverness
Banff
Kinnaird Hd
Peterhead
Aberdeen
Stonehaven
Montrose
Arbroath
Dundee
Perth
Oban
Inverary
Stirling
Kirkcaldy
Leith
EDINBURGH
Dunbar
Eyemouth
Berwick
Greenock
Glasgow
Ayr
Craster
Blyth
Newcastle
Sunderland
Wigton
Maryport
Whitehaven
Hartlepools
Middlesbrough
Whitby
Scarborough
Flamborough Hd
Morecambe

same locality as that in May - at E14b on VS(13)15. There is doubtless a relationship between the fresher water in both months, that in June being either a relic of that in May or representing a water movement that has persisted over the period. The latter supposition is more probably correct, as the salinity in June is lower even than in May.

Temperature is broadly inversely proportional to depth, ranging from over 10°C. at the surface to less than 7°C. at the bottom.

VS(13)18 extends from the Fisher Bank to May Isle and is therefore practically coincident with the May section VS(13)16.

The salinity distribution is almost featureless. After remaining more or less uniform at $34.97^{\circ}/oo$ in the eastern half of the section, salinity falls off steadily westwards. Temperature, apart from a slight lowering in the upper layers in the west, increases from less than 7°C. on the bottom to more than 9° on the surface - the same bottom temperature, but a cooler surface, than in the centre of the area as shown on VS(13)17.

The complete data for the Middle North Sea are presented in T-S curve form on TS(13)5 and 5a. The positions of stations not appearing on sectional diagrams are shown on Figure 20.

April. Curves 4, 6, 11, 16 and 21 (on the transparency) represent stations worked in April and situated off the Scottish coast. Salinity is for the most part between $34.50^{\circ}/oo$ and $34.60^{\circ}/oo$ with a tendency for maxima to occur at the bottom. Temperature is at its lowest - 5.25°C. to 6.5°C. - a very limited range. Curve 16 shows lower salinities than the others and as it is nearest May Isle, the freshening may/

may be attributed to Scottish coastal water.

May. The May curves depict conditions at the same stations as were worked in April, together with those comprised by VS(13)15 and 16. Curves 5, 7, 9, 12, 13 and 25, representing stations in much the same positions as the April series, form a group at $34.40^{\circ}/oo \times 6^{\circ}-7^{\circ}C$. There is thus a decrease in salinity and increase of $1^{\circ}C$. in temperature in this east coast area since the previous month. In the western area of the Northern North Sea a similar decrease of salinity took place in the early part of the year.

The bottoms of curves 29, 31 and 32 form a small concentration at $34.90^{\circ}/oo-35.00^{\circ}/oo \times 5.75^{\circ}-6^{\circ}C$. The stations to which these curves pertain are indicated on Figure 19 by B', since this water may reason-:ably be assumed to be closely related to the B type in the Northern North Sea, which it resembles in salinity, temperature and date. A June curve, 33, runs to bottom in the B' group, showing that some at least of that water-type maintains its character from May to June.

June. The June stations are all represented on the vertical sections. The T-S curves show only one grouping - of bottoms of curves at $35.00^{\circ}/oo \times 6.5^{\circ}-7^{\circ}C$. These stations are east of $2^{\circ}E$. and there-:fore not comparable with other stations in 1913.

July. There are only two July curves - numbers 18 and 20 - characterised by high temperatures surface and bottom and by a large thermal range.

August. The mean of a series of observations taken at a point $57^{\circ}N$. $0^{\circ}E$. is shown by curve 27, which closely resembles the July curve 20.

November. The November curves, 8, 15 and 19 are characterised by low range of temperature at each station and illustrate the retardation/

retardation of the temperature cycle in the sea, particularly in the lower layers, surface and bottom temperatures alike being from 10° to 11°C.

Summary of Hydrographic Conditions
in the North Sea in 1913.

The hydrography of the North Sea in 1913 is marked by the poverty of Atlantic water.

The north-western area, usually flooded by highly saline water, was subject for the most part to influence from Scottish coastal water rather than Atlantic, except for a feeble influx of the latter which occurred in July.

Baltic or Continental water, on the other hand, spread unusually far west in July, doubtless as much from lack of opposition as on account of its own abundance.

The lower layers in the centre of the area, as in former years, were occupied by water which retained relatively fresh and cold conditions from spring into summer.

THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS

DURING THE YEAR 1914.

THE HYDROGRAPHY OF THE NORTHERN NORTH SEA AND CONTIGUOUS REGIONS. DURING THE YEAR 1914.

The courses traversed by the Scottish research vessel while engaged in hydrographic work in 1914 differ considerably from those in the three preceding years. Many of the lines of stations formerly visited annually or oftener are omitted, notably the Faroe-Shetland Channel and Southern Norwegian Sea lines. Hydrographic operations for the year 1914 were effected almost entirely in four cruises; one in April, with, in addition, a few stations before and after it in the Moray Firth area; one in the first half of June; one in the second half of the same month, and finally, one in July. During each of these cruises, the stations were for the most part those generally worked, but they were not visited in the usual order, the research vessel changing course often and laying down stations so situated that many can be incorporated in more than one sectional diagram, while horizontal charts can profitably be constructed from the material obtained on each of the four cruises. Thus while the data are more restricted in time and position, they afford perhaps a better picture of hydrographic conditions in the North Sea in proportion to their volume than do the data for preceding years.

Since the great bulk of the data pertains to one region, those in other areas being in the nature of appendages to the main cruise in the Northern North Sea at the same time, the primary classification by regions adopted in the treatment of the material for 1911, 1912, and 1913 is discarded and what was the secondary division in those years, namely the time factor, is given first place.

The cohesion in time and place of the data derived from individual cruises and their distinct separation in time from the other cruises allows of the hydrographic conditions as shown graphically by the vertical sections, horizontal charts and T - S diagrams being examined cruise by cruise.

F I G U R E 21.

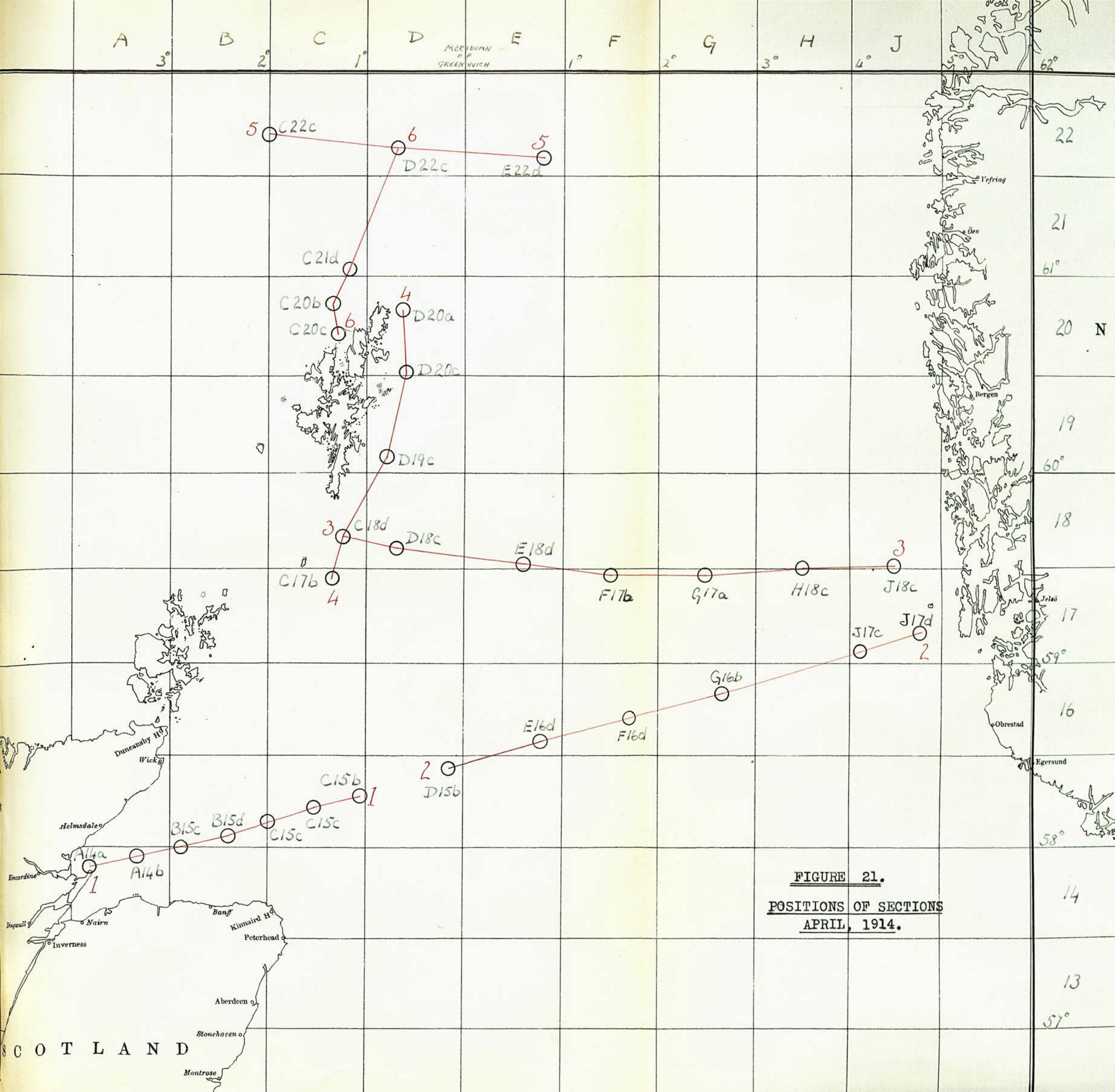


FIGURE 21.

POSITIONS OF SECTIONS
APRIL, 1914.

THE APRIL CRUISE.

The positions of the hydrographic sections constructed from the data collected in April are shown on Figure 21.

Unusually high salinities appear on VS(14)1, attaining 35.35‰ at the bottom of C15c, and 35.37‰ at the surface of C15b. Salinity falls off rapidly westwards to 34.80‰, and thereafter the decrease is very much slower, the region of closely packed isohalines between C15c (2°W) and C15c (1°32 W) being the boundary zone of mixing between the very salt water in the east and the uniformly fresh water in the west. The same regional division appears in temperature, which exceeds 7°C only in the surface layers west of 2°W, but at all levels in the highly saline water.

VS(14)2 continues the line of VS(14)1 to Norway after an interval of 8 days. Maximum salinity is recorded at the westmost station, where it rises to 35.30‰. Eastwards salinity decreases slowly, while at F16d temperature falls below 7°C. The axis of an Atlantic influx of unusual vigour evidently lies somewhere between C15b on VS(14)1 and D15b on VS(14)2.

At the bottom of J17c salinity exceeds 35.20‰ and nearby the temperature rises above 7°C. This is a trace of Atlantic water analagous to that of much greater volume found in May 1912 in this eastern side of the Northern North Sea.

Eastwards from F16d to G16b and in the lower layers beyond, salinity and temperature are very uniform at 35.10‰ and just under 7°C. Baltic or Continental water, with a minimum salinity of only 30.61‰ at the surface of J17d, occupies the upper and eastern water layers. Temperature in this very fresh water is also low, sinking to 4.56°C at 10 m at J17d, but increasing downwards. The concurrent increase of salinity is effective, however, in maintaining stability in the water-column.

Practically contemporaneous with, and parallel to the foregoing section, is VS(14)3, which extends from Fair Isle to Norway.

The Atlantic influx to the North Sea appears in cross-section at the two west-most stations. The nucleus of the Atlantic water in the North Sea generally lies at the bottom, but on VS(14)3 it occupies the upper 50 m at D18c, where temperature and salinity (apart from a single observation of 35.45‰ at 20 m on C18d) are at a maximum. The result is inversion of density in the water column at this station.

Eastwards from the Atlantic water salinity decreases slowly and uniformly to F17b where, also, temperature falls below 7°C. Beyond this, in the deep trench, a salinity of 35.30°/oo is recorded at the bottom of H18c and in the layers above and to the east of it, temperature exceeds 7°C. This water, like that in a similar position on VS(14)2, is to be regarded as of Atlantic derivation, though more distantly related than that in the west.

The upper layers in the east consist of cold fresh Baltic water with similar minima , namely, 30.91‰ and 4.86°C, to those on VS(14)2.

VS(14)4 lies along the east side of Shetland and shows that even in this inshore position the water is of Atlantic character. Salinity everywhere exceeds 35.25°/oo and in intermediate levels at D20c, and in the upper layers in the south, 35.30°/oo is surpassed. Instability is again brought about and is probably connected with the vigour of the Atlantic inflow, as indicated by the high salinities.

Temperature decreases from north to south and from surface to bottom, confirming the assumption that the Atlantic water is moving into the area from the north and not directly from west of Fair Isle, as the high salinities in the south of the section might suggest. These are doubtless due rather to the right-hand deflection of the south-going Atlantic Stream in this locality in a manner similar to that found on various occasions in previous years.

The westmost three stations of the usual Southern Norwegian Sea section appear on VS(14)5. Atlantic water with a temperature exceeding 8°C floods the part of the Continental Shelf shown and also the upper 300 metres of the water - column at C22c. This is a greater depth than at this station in the preceding years, as shown by the following table.

Table IX

Atlantic Influence at Station C22c
in the years 1911-1914.

Month	Year	Depth of 35.25°/₀₀ isohaline (m)	Depth of upper surface of bottom Norwegian Seawater (m)
May	1911	125	400
"	1912	Surface only	300
July	1913	absent	300
April	1914	300	500

Atlantic influence is thus evidently well above normal in April 1914 in the open sea at C22c as well as in the Northern North Sea.

Below 500 m at C22c, also a deeper level than in 1911, 1912 and 1913, the usual cold fresh bottom Norwegian Sea water supervenes.

VS(14)6 shows very salt water close in to the north-west side of Shetland, much of it exceeding $35{\cdot}35\,^{\circ}/_{oo}$ in salinity and attaining even $35{\cdot}41\,^{\circ}/_{oo}$. The Atlantic stream in a concentrated form thus washes the west side of Shetland with no intervening buffer of fresher north-west Scottish coast water on its right flank as is often found.

The mode of entry of the Atlantic water to the North Sea is clearly illustrated on the horizontal charts HC(14) 1-4.

The axis of the Atlantic water lies off the east side of Shetland, where, on all four charts, salinities exceeding $35{\cdot}30\,^{\circ}/_{oo}$, and at 100 m, over $35{\cdot}40\,^{\circ}/_{oo}$, are to be found.

Between this and Shetland is slightly fresher water, less than $35{\cdot}30^{o}/_{oo}$ but always salter than $35{\cdot}20^{o}/_{oo}$. Since no salinities less than $35{\cdot}30^{o}/_{oo}$ occur on the north-west side of Shetland this freshening is evidently not due to north-west Scottish coast water rounding Shetland on the right flank of the Atlantic stream, but seems rather to come from the south. The Moray Firth may be the source from which the freshening proceeds, but there is also the possibility of north-west coast water reaching the north-east of Shetland from south of Sumburgh. If there is a stream of fresher water from the Moray Firth or the north-west coast it must be quite narrow. On the other hand, the lower salinities off the east of Shetland may simply be a relic of fresher water which occupied a greater area earlier in the year and which the Atlantic pulse has not swept out owing to the sheltering effect of Shetland.

Whatever the origin of this fresher water, it serves to show something of the course taken by the Atlantic stream. At all depths a spur of slightly fresher water (less than $35{\cdot}30^{o}/_{oo}$) projects some 20-30 miles north-eastwards from Unst, showing plainly that the Atlantic water does not turn immediately round the north of Shetland. At the surface, 20 and 50m, salinity varies only slightly off the north of Shetland, but at 100 metres, where the $35{\cdot}40^{o}/_{oo}$ isohaline appears, the course of the Atlantic water can be more definitely traced. On HC(14)4, showing the plane of 100 metres, the axis of saltest water in the Faroe-Shetland Channel is some 15 miles north-west of Unst. Unfortunately the data do not permit of this water being followed without interruption, but when it appears again, the lobe of $35{\cdot}40^{o}/_{oo}$ water points S.S.W. in the sub-rectangular area E19a. The Atlantic water evidently passes well across the opening between Shetland and Norway before swinging completely round from a north-easterly direction to a south-westerly.

In the centre of the Northern North Sea, the eastern boundary of the Atlantic influx, as defined by the

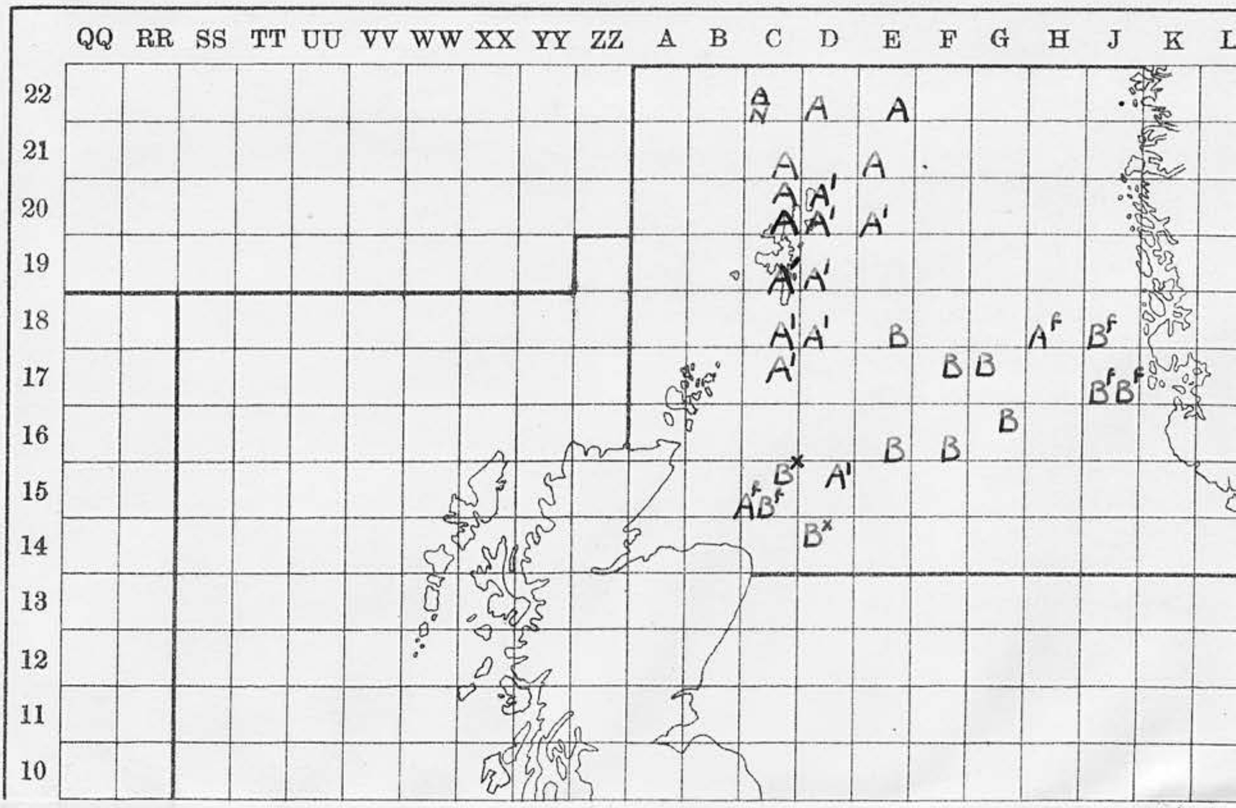


Figure 22.

Distribution of water-types, April 1914.

Salinity and temperature of the water-types shown on Figure 22, together with the positions and dates of the stations whose T-S curves make up the groupings which represent the above types.

A

35.30-.40 °/oo x 8-9°C)

	TS(14)1a		
(A/N)	14	C22c	21/4
	15	C21d	21/4
	16	C20b	25/4
	17	C20d	25/4
	26	D22c	22/4
	34	E22d	22/4
	35	E21c	21/4

A'

(35.28 °/oo x 7-8°C)

TS(14)1		
18	C19d	17/4
19	C18d	17/4
20	C17b	17/4
f 24	C15c	4/4
27	D20a	25/4
28	D20c	20/4
29	D20c	21/4
30	D19c	17/4
31	D18c	16/4
32	D15b	12/4
36	E20c	20/4
f 43	H18c	16/4

B

(35.10-.20 °/oo x 7°C)

TS(14)1a		
× 22	C15b	4/4
f 23	C15c	4/4
× 33	D14a	29/4
37	E18d	16/4
38	E16d	12/4
39	F17b	16/4
40	F16d	12/4
41	G17a	16/4
42	G16b	12/4
f 44	J18c	15/4
f 45	J17c	13/4
f 46	J17d	13/4

isohaline of $35 \cdot 20^{o}/_{oo}$, more or less coincides at all depths with the meridian of $0^{o}30'$E.

The April data appear in the form of T-S curves on TS(14) 1 and 1a, the separation into two diagrams showing that the apparently formless mass of the complete set of curves obtained by superimposing TS(14)1a on TS(14)1 is in reality composed of a number of groups of depth - marks representing water-types.

Of these groups, the most saline is that on TS(14)1a with salinity $35 \cdot 30^{o}/_{oo}$ to $35 \cdot 40^{o}/_{oo}$ and temperature 8-9°C. This cluster is composed of whole curves, except for No. 14, representing station C22c, which with bottom Norwegian Sea water in its lower layers, passes downwards out of the group. This group represents the most concentrated Atlantic water in the area and on Figure 22, where its presence is indicated by the letter A, it lies off the north and west of Shetland but does not enter the North Sea.

On TS(14)1 there is a second group, with somewhat lower salinity and temperature - $35 \cdot 28^{o}/_{oo}$ and 7-8°C. This type is plotted as A' on Figure 22, where it is obviously the representative of the Atlantic water in the Northern North Sea, that is, modified A water. The position on the T-S diagram of the A' group, namely, on the line joining the under side of the A cluster to the upper surface of the bottom Norwegian Sea water with co-ordinates near the normal of $34 \cdot 92^{o}/_{oo} \times 3^{o}C$ shows that the A' type is derived from the Atlantic water by a dilution of bottom Norwegian Sea water.

The transition from the A to the A' type off the north-east of Shetland is abrupt and VS(14)5 shows that the North Sea plateau off Shetland is flooded at all depths by pure Atlantic water. The A water, therefore, evidently does not pass directly south into the North Sea, but must pursue a course such that it passes over an area where mixing with bottom Norwegian Sea water is possible.

Previous years observations have shown that such conditions are generally to be found on the Continental Slope north of the Viking Bank. The conclusion drawn from the horizontal charts, that the Atlantic water passes well across towards Norway before turning back to the east side of Shetland, is thus borne out by the T-S diagrams.

A third group with salinity $35{\cdot}10^{o}/oo$-$35{\cdot}20^{o}/oo$ and temperature $7^{o}C$, B on Figure 22, can be distinguished on TS(14)1a, but this type does not include the complete water-column at a station as do the A and A' types, but is rather a bottom type. Curves 44 and 46 have low surface salinities due to Baltic water and the trend of these two curves gives the line of mixing between the very fresh and somewhat cold Baltic water and the A type. The B group lies on this line and would therefore appear to be a product of mixing between modified Atlantic and Baltic water, though on account of the wide area covered by this type the mixing process would require to have been active in the months prior to April.

The four curves in the B group with low surface salinities are represented on Figure 22 by B^{f}, and two stations with modified B water, by B^{x}. It is doubtful whether the latter two stations, C15b and D14a, are truly of B type, since they are separated from the main block of B water by A' water at D15b. On the other hand, the Atlantic influx may have split the mass of B water. This suggestion bears out the hypothesis that the B water was formed mainly before the entry of the April influx of Atlantic water.

The Moray Firth stations show little of interest save the group formed by curves 1, 7, 8 and 9 whose common features are doubtless due to their position opposite the Pentland Firth, where tidal mixing will tend to smooth out variations of temperature and salinity.

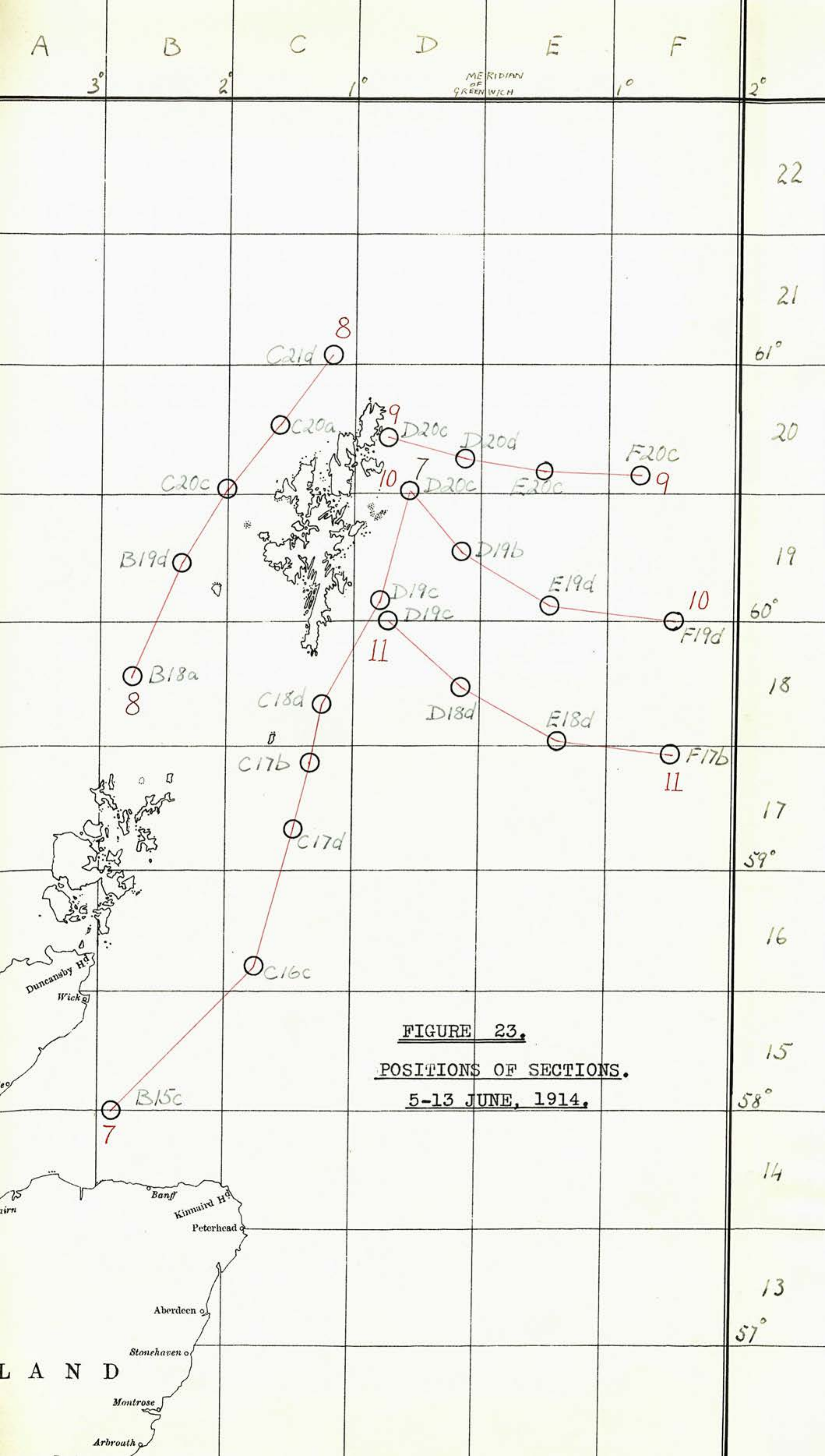


FIGURE 23.

POSITIONS OF SECTIONS.

5-13 JUNE, 1914.

THE FIRST JUNE CRUISE

The vertical sections constructed from the cruise between the 5th and 13th June can be located on Figure 23.

VS(14)7 is the Lossiemouth to Fetlar line. Salinity off Shetland has increased since April to $35{\cdot}34^{0}/_{00}$ at D20c. Temperature also, while uniform as in April, is higher overall by $1^{\circ}C$. Since this increase takes place at all depths, it is to be regarded as due to renewal of the water from a warmer source - the Atlantic - and not by insolation,which warms only the upper layers.

Atlantic water reaches just south of C17b, beyond which salinity falls off steadily, except for a pool of less than $35{\cdot}10^{0}/_{00}$ water at C17d suggesting north-west Scottish coast or Moray Firth influence.

Conditions on the opposite side of Shetland are shown on VS(14)8. Similarly high salinities to those in April obtain, but temperature has risen almost $2^{0}C$. The absence of north-west coast water at the south end of this section, where it was generally found in the three former years, is to be noted as an indication of the abundance of Atlantic water in the Faroe-Shetland Channel in June 1914.

VS(14) 9, 10 and 11 are a set of sections running east to south-east from Shetland.

Highest salinities occur on the northern section, VS(14) 9, where, except at D20c, salinity exceeds $35{\cdot}30^{0}/_{00}$ and attains even $35{\cdot}37^{0}/_{00}$. Only the western half of VS(14)10 and the westmost station of VS(14)11 reach a salinity of $35{\cdot}30^{0}/_{00}$.

Temperatures also decrease southwards, the 8 and $9^{0}C$ isotherms rising nearer the surface and the former extending further west with lower latitude.

Atlantic influence thus diminishes southwards, though to a less degree near Shetland than further offshore.

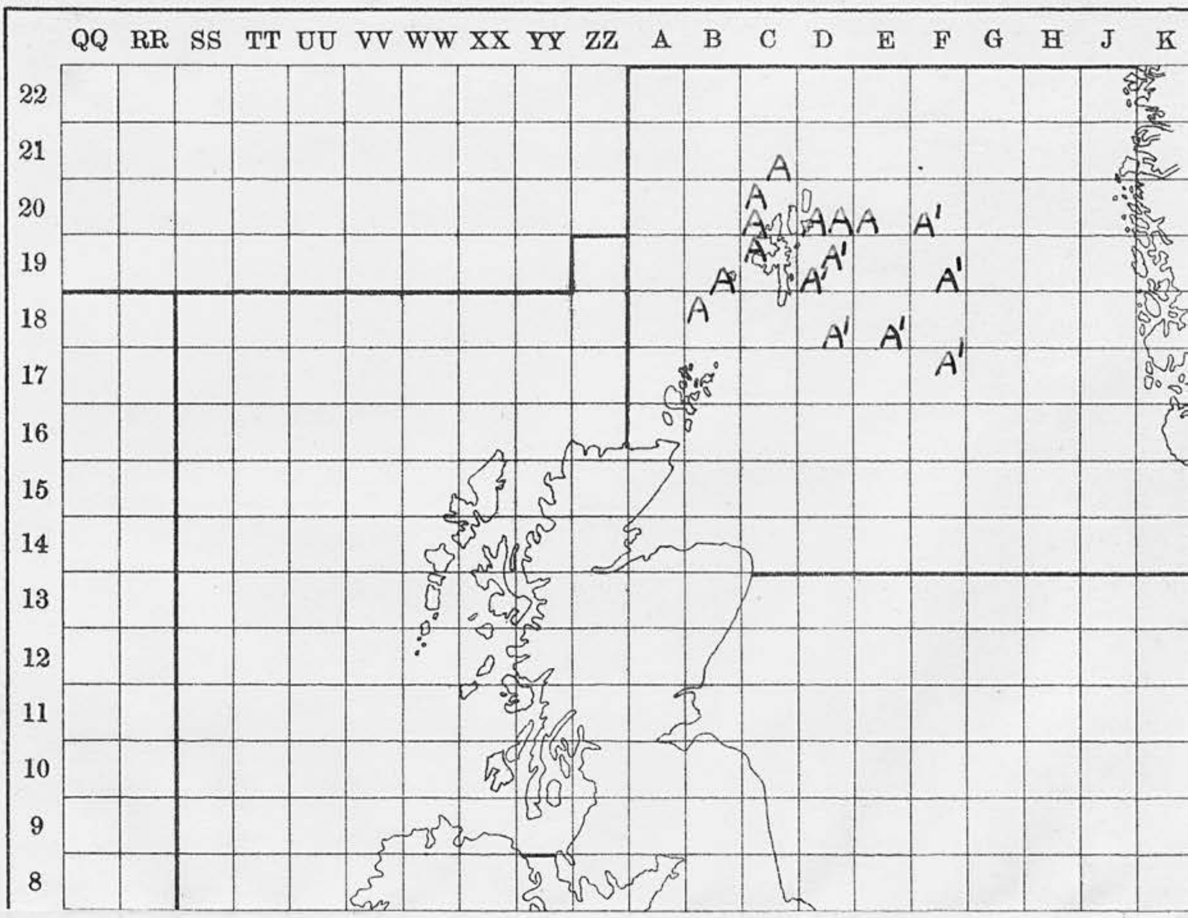


Figure 24.

Distribution of Water-Types, 5-13 June 1914.

Salinity and temperature of the water-types shown on Figure 24, together with the positions and dates of the stations whose T-S curves make up the groupings which represent the above types.

A

(35.30-.35 $^{0}/_{00}$ x 8-9°C)

TS(14)2a

1	B19d	12/6
2	B18a	13/6
4	C21d	12/6
5	C20a	12/6
6	C20c	12/6
7	C19a	12/6
12	D20c	9/6
14	D20d	11/6
19	E20c	11/6

A'

(35.25-.35 $^{0}/_{00}$ x 7-8°C)

TS(14)2

15	D19b	8/6
16	D19c	6/6
17	D19c	8/6
18	D18d	9/6
20	E18d	9/6
21	F20c	11/6
22	F19d	10/6
23	F17b	10/6

The horizontal charts HC(14)5-8 constructed from the observations made between the 5th and 13th June show that the Atlantic water in the North Sea has neither such volume nor does it extend so far south as in April. This recession northwards of the $35{\cdot}30^{o}/_{oo}$ and $\cdot 20^{o}/_{oo}$ isohalines, together with the massive shape of the area of highly saline water as contrasted with the lobate form of the corresponding isohalines in April indicates that the Atlantic pulse in progress at that time has been spent, and that now in the first part of June, the fresher waters of the North Sea are in process of reducing the high salinities brought by the April influx.

At the surface, 20, and 50 metres it is to be noted that both salinity and temperature are higher west of the Fair Isle - Sunburgh Hd. passage than to the east of it. There is evidently, then, no general movement of water from west to east through this channel.

The foregoing conclusion regarding the Atlantic water is substantiated by the T-S diagrams TS(14)2 and 2a.

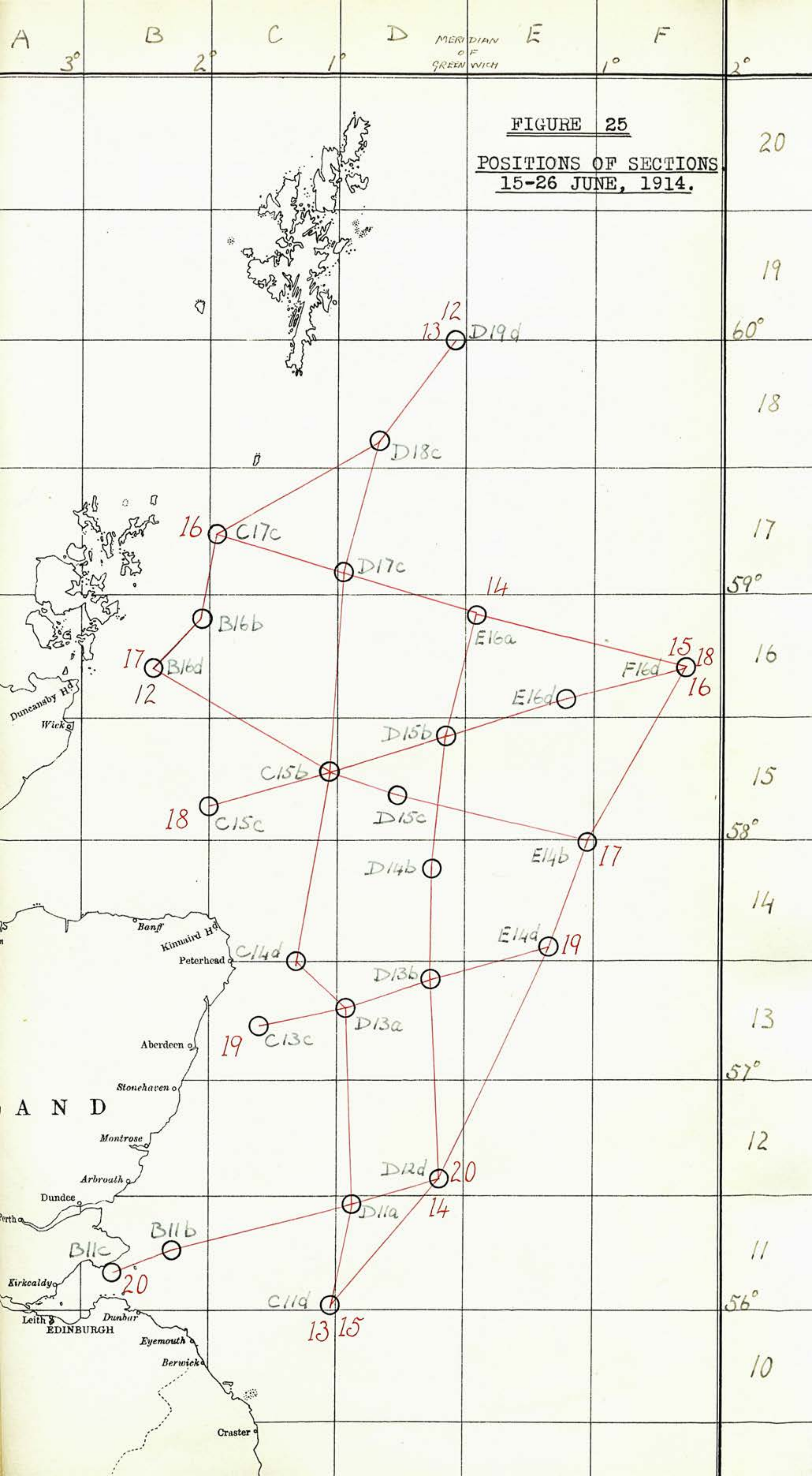
The use of a transparency shows clearly that the curves are of two types, those on TS(14)2a having bottom salinity and temperature of $35{\cdot}30^{o}/_{oo}$-$35{\cdot}35^{o}/oo$ x 8-9°C, while the lower ends of most of the curves on TS(14)2 form a group at $35{\cdot}25^{o}/oo$-$35{\cdot}35^{o}/oo$ x 7-8°C. The main distinguishing factor, it will be noted, is temperature, the salinity limits overlapping. The positions of the two types are shown on Figure 24 by the symbols A and A' respectively.

The distribution of water-types is comparable to that in April, except that the pure Atlantic water A occurs as far south as lat. 60° 30' N on the east side of Shetland. The Atlantic stream on Figure 24 therefore appears to be swinging more or less directly round the north of Shetland

The similar salinities of the two types, also, shows that the modifications from A to A' is not due to dilution by bottom Norwegian Sea water as is generally the case. The inability of the Atlantic stream to perform its usual transit of the Southern Norwegian Sea prior to entering the Northern North Sea is further indication of its feebleness in the early part of June.

FIGURE 25

POSITIONS OF SECTIONS 15-26 JUNE, 1914.



THE SECOND JUNE CRUISE.

The second June cruise, between the 15th and 26th, is more extensive than the first, but as shown by Figure 25 on which the positions of the sections are given, the area covered lies for the most part south of that traversed in early June. The sections are of two main types, those approximately meridional and those running more or less east-west: the former class will be examined first.

VS(14)12 lies just east of Orkney and Shetland. Atlantic water appears in the north, the lower layers at D18c and all depths at D19d having salinities exceeding 35·30°/oo, with a maximum of 35·43°/ oo at 20 m on D19d, causing inversion of density. Salinity falls off fairly rapidly southwards at first, but under - 35·00°/oo water occurs only at the southmost station. Temperature is highest, surpassing 11°C, in the upper layers in the south. In the north, the salt water in the lower levels has the lowest temperature, less than 8°C.

VS(14)13 shares its two north-most stations with VS(14)12. Southwards from the Atlantic water in the north salinity diminishes gradually, but between C15b and C14d the decrease is rapid, after which the gradient is again slight. Surface temperature is highest in the south, exceeding 12°C, while in the north 11°C is not attained. Bottom temperature is less than 8°C except round D13a and C14d, where it is 8-9°C. The thermal gradient is steep between 10 and 30 metres deep in the south.

Atlantic influence seems to be felt as far as C15b, while the adjacent zone with crowded isohalines and higher bottom temperatures is doubtless the boundary along which mixing is in progress with the fresher water to the south.

On VS(14)14, also, the saltest water is in the north, just exceeding a salinity of 35·20°/oo.

After a slow decrease to D14b, the isohalines crowd together between this station and D13b. This latter zone, like its analogue on VS(14)13 is that in which the Atlantic water marches with the fresher North Sea water.

Surface temperature, as in the previous section, diminishes from over 12°C in the south to under 11°C in the north, while bottom temperatures are all under 8°C, though there is less of this cool water in the zone of mixing than on either side of it.

Salinity on VS(14)15 attains a maximum of only 35·19‰ in a body of over - 35·10‰ water in the lower layers in the north, away from which salinity falls off smoothly, there being practically no sudden drop as on the two preceding sections. The 12°C surface temperature in the south is 1°C higher than that in the north, and with increase of depth, temperature diminishes to 8°C at 50 metres.

This section, VS(14)15, seems to be almost outwith the area subject to Atlantic influence, since there are only traces of highly saline water and a very slightly marked zone of mixing on its southern side.

The first of the east-west sections, VS(14)16 has modified Atlantic water with salinity slightly over 35·20‰ at the two middle stations. Fresher water lies on both sides, with indications of Scottish coast water on the surface in the west and of Continental water at similar levels in the east. Surface temperature attains 11°C in the east and west, while the Atlantic water is 1°C cooler. The lower layers have a temperature less than 8°C except in the west.

Very little water exceeds a salinity of 35·20‰ on VS(14)17, but the 35·10‰ isohaline encloses a considerable area. The upper layers at the ends of the section, as in the previous line, show indication in the west of fresh Scottish coastal water and in the east of Continental water.

The thermal distribution also is similar to that of VS(14)16, except that surface temperatures everywhere reach 11°C.

VS(14)18 depicts hydrographic conditions on the Moray Firth line of stations. There is present a body of over 35·10°/oo water analagous to that on the previous section, but with a maximum salinity of only 35·17°/oo at D15b. In respect of fresher water at both ends and in its thermal distribution, this section resembles the foregoing pair.

VS(14)19 shows the zone of mixing which occurred also on the meridional sections, while on VS(14)20 a distinct hydrographic region is depicted. The low salinities indicate absence of direct Atlantic influence and surface temperatures are high, with a steep thermal gradient between 10 and 30 metres.

Hydrographic conditions between the 15th and 26th of June are illustrated more comprehensively on the horizontal charts HC(14)9-12.

Once again the isohalines assume lobe-formation, indicating more active circulation, and the Atlantic water as outlined by the isohalines of 35·20°/oo and 35·30°/oo extends further south than at the time of the first June cruise, but not so far south as in April.

The 35·20°/oo isohaline has moved relatively further south than the 35·30°/oo has, a circumstance which probably means that a new Atlantic pulse is just gathering momentum, the highly saline water beginning to advance and, mingling with the water in front of it, creating a greater amount of water of intermediate salinity (35·10°/oo-35·30°/oo).

The above view is supported by the fact that the isotherms behave in an apparently inconsequent manner, indicating, it would seem, that the previously - established thermal distribution has been upset and that a new one in relation to the advancing salt water has not yet arisen.

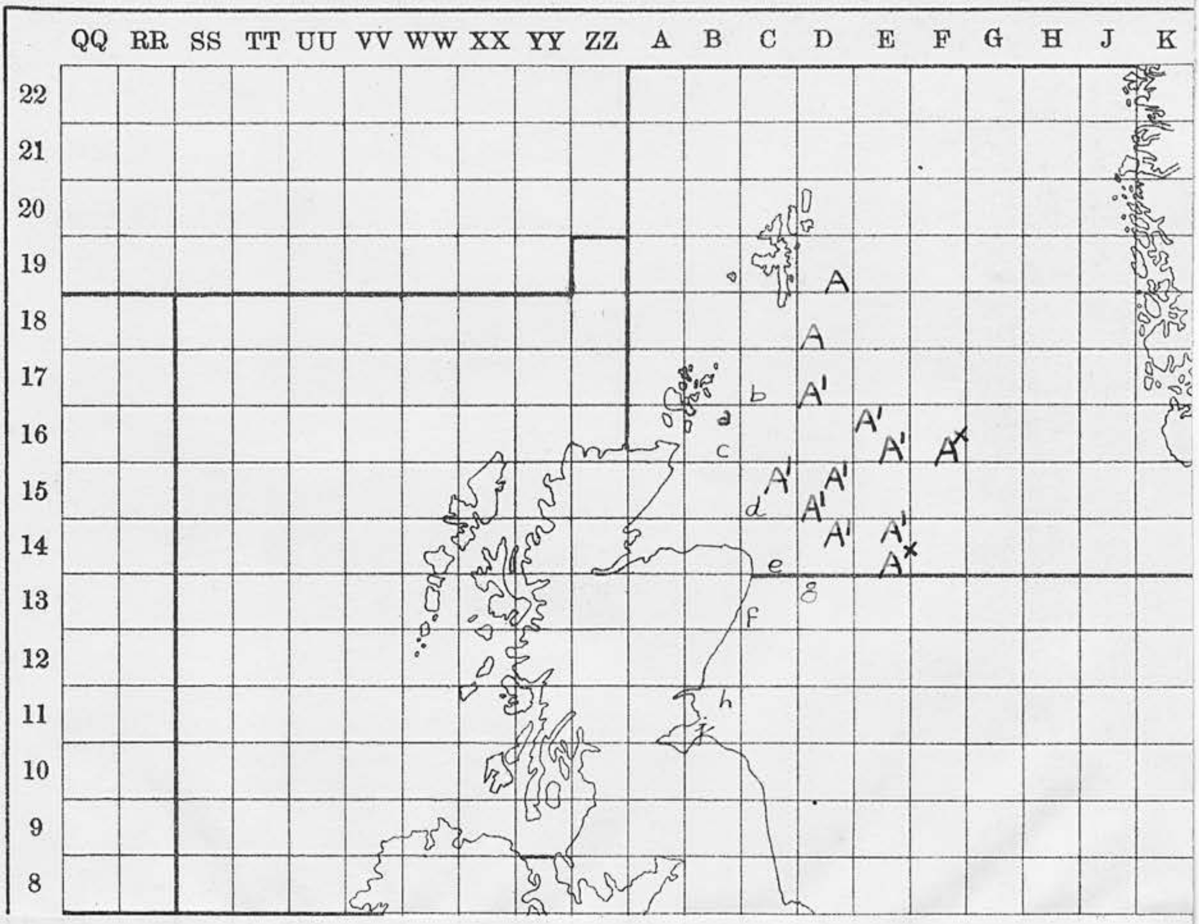


Figure 26.

Distribution of Water-Types, 15-26 June 1914.

Salinity and temperature of the water-types shown on Figure 26, together with the positions and dates of the stations whose T-S curves make up the groupings which represent the above types.

TS(14)3

A

($35.30^{0}/oo \times 7.5^{0}C$)

12	D19d	15/6
13	D18c	15/6

A'

($35.10-.25^{0}/oo \times 7-7.5^{0}C$)

6	C15b	17/6
14	D17c	16/6
15	D15b	24/6
16	D15c	17/6
17	D14b	25/6
22	E16a	16/6
23	E16d	24/6
24	E14b	23/6
×25	E14d	23/6
×26	F16d	24/6

a, b, c. . . . . . .

(Salinity varies)
(bottom $9^{0}C$)

a	1	B16b	16/6
b	5	C17c	16/6
c	2	B16d	16/6
d	7	C15c	17/6
e	8	C14d	25/6
f	9	C13c	19/6
g	18	D13a	19/6
h	3	B11b	26/6
j	4	B11c	26/6

The isohalines of $35 \cdot 10^{o}/oo$ and $35 \cdot 20^{o}/oo$ show that the Atlantic influx swings round from a southerly direction in the north-west to an almost easterly course on approaching the Buchan coast. The 50 fathom contour at 57°30'N appears, as in 1911, to form a boundary between two different hydrographic regions, that to the north being subject to Atlantic influence, and that to the south having uniformly low salinities.

The comparative lack of association between temperature and salinity in the area covered by the second June cruise is reflected in the scattering of the curves on the T-S diagram TS(14)3.

The bottoms of a number of curves, however, group themselves between rather wide salinity limits of $35 \cdot 10^{o}/oo$ and $35 \cdot 25^{o}/oo$ with temperatures from 7°C to 7·5°C. The occurrence of stations with water of this type in their lower layers is shown by A' on Figure 26, the index being added to the name-letter because two curves Nos 12 and 13 have purer A water. This latter type lies off the east of Shetland and the A' type in what is generally found to be the track of an Atlantic influx to the North Sea. Two stations (curves 25 and 26), whose bottom salinities do not quite justify their inclusion in the A' type, are indicated by A^{x}. These transitional stations are at 57°30'N and in the centre of the Northern North Sea respectively.

The remaining curves on TS(14)3 can be arranged in two series. One has bottom temperatures of almost 9°C but a wide variation of salinity. These stations are plotted on Figure 26 as a, b, c -----etc. in order of decreasing salinity. They lie between the A' type and the Scottish coast, the warming influence of which, together with tidal mixing, doubtless accounts for the higher bottom temperatures.

The second series has bottom temperatures similar
:hose of A', or slightly higher, but with the warmest
face water appearing on the diagram. Salinity again
ies, from 34·60°/oo to 34·80°/oo. These stations lie
the Middle North Sea and their high surface temperatures
be explained by solar warming, due not only to lower
:itude, but to relative quiescence of the water. The
inity is simply that of the North Sea complex.

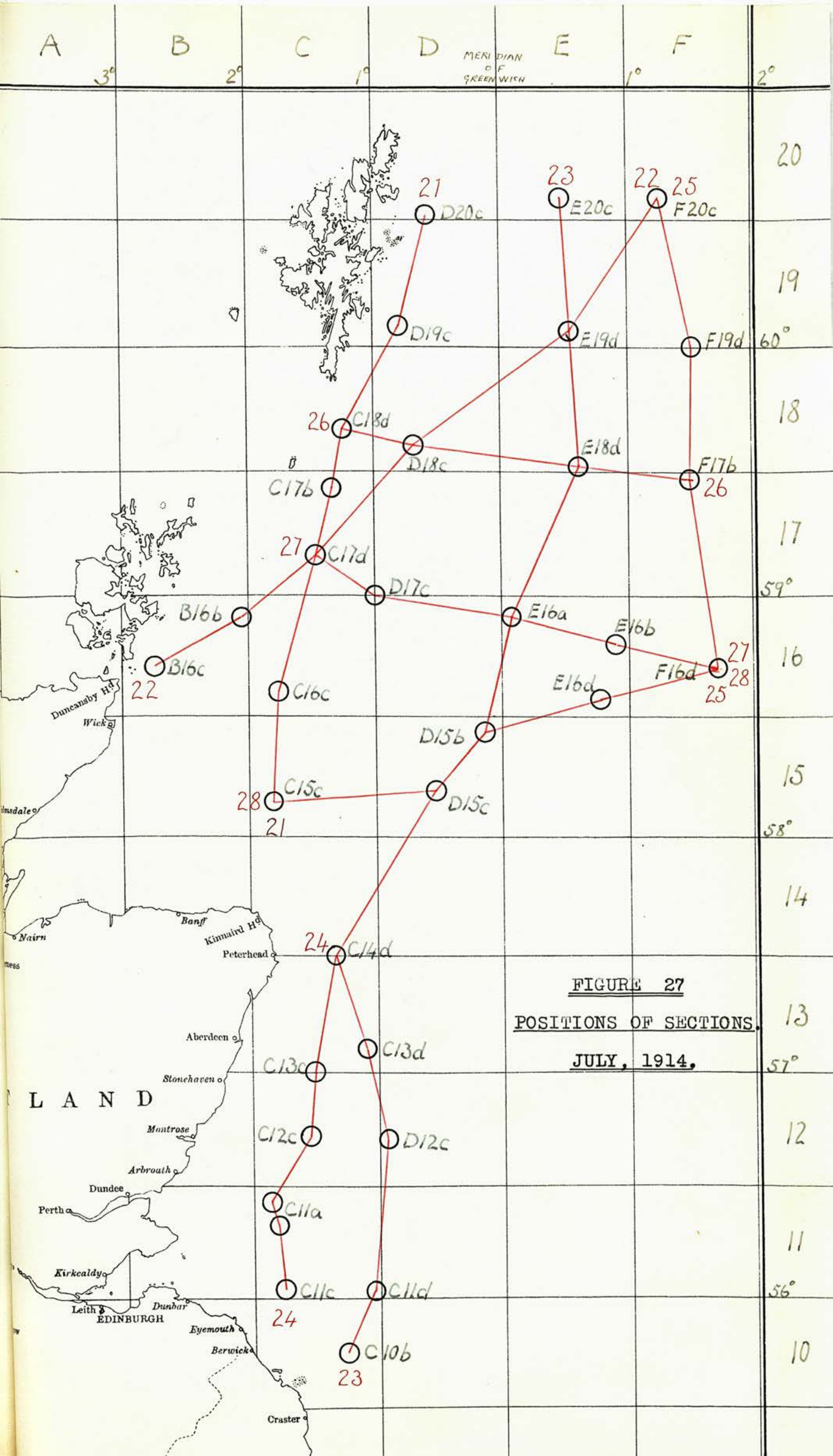


FIGURE 27

POSITIONS OF SECTIONS.

JULY, 1914.

THE JULY CRUISE

The July cruise is slightly more extensive than the previous one in the second part of June, but as was the case in the latter, the data form vertical sections of two classes, one north-south, the other east to west. The positions of these are shown on Figure 27.

The most westerly of the meridional sections is VS(14)21, on the Aberdeen-Shetland line. Atlantic water abounds on this section. Salinity in the extreme north stands at the high level of $35 \cdot 37^{o}/oo$ and exceeds $35 \cdot 25^{o}/oo$ as far south as C16c. There is strong indication in the upper layers of a movement northwards of fresher water, similar to that often found on this line in previous years.

Temperature has risen to over $11^{o}C$ on the surface everywhere except at C18d. The bottom is warmer than $8^{o}C$, while at C18d and C17b it surpasses $9^{o}C$.

The high salinities and warming of the bottom layers indicate that an Atlantic influx has taken place since the time of the previous cruise. The low range of temperature at C18d, as in former years, is doubtless the outcome of tidal mixing in the Fair Isle-Shetland Channel.

VS(14)22 has salinities for the most part above $35 \cdot 20^{o}/_{oo}$ with a maximum of $35 \cdot 35^{o}/oo$ in the north. Fresher water, however, appears on the surface at the southmost station.

Surface temperature is higher than on the preceding section, attaining $13^{o}C$ at E19d, while the bottom in the northern half is below $8^{o}C$. The thermal range in the north, near open-sea conditions, is less. Thus though the high salinities reveal the presence of Atlantic water, the wide vertical temperature range over most of the section, involving a steepened thermal gradient in the upper 30 metres, suggests that the momentum of the influx is spent and that the salt water is now relatively motionless, allowing full play to solar warming of the surface layers.

South of D18c the difference between surface and bottom temperatures is less, owing to the influence of mixing caused by the tides on the adjacent coast.

VS(14)23 provides a section of the North Sea from the north of Shetland to Holy Isle. Water exceeding 35·30°/oo salinity and with a maximum of 35·35°/oo appears only in the north, but the Atlantic influence as limited by salinities of 35·25°/oo reaches south to D15b. Beyond this station there is a zone of mixing to C14d, south of which salinity is low and irregular. Fresh water appears, moreover, to be proceeding northwards in the upper layers from the Middle to the Northern North Sea.

Surface temperature in the Atlantic water is even higher than on VS(14)21, exceeding 13°C and even 14°C in the slightly fresher water at D15b. The bottom temperature is again below 8°C and the thermal gradient is over-steepened in the upper 50 m, but as on VS(14)22 the range is less at the northmost station.

In the Middle North Sea, that is, south of C14d, the thermal distribution is complex. The southmost stations have a wide range of 7°C while at D12c and C13c the difference between surface and bottom is less than 3°C. Eddying is suggested at these latter two stations.

VS(14)24 is west of the southern part of the preceding section and as the stations vary in date to a maximum of 11 days, this diagram must be used with caution.

Both salinity and temperature distribution is irregular. C11a (56°26'N) and C13c are outstanding in that they have a much smaller range of temperature than at the adjacent stations. The difference in date does not account for this; on the contrary, since the two stations in question are the most recently worked, the time interval should rather have reduced the disparity between them and their neighbours.

Some complicated eddying seems to be in progress off Fife.

Though VS(14)25 lies some 30-40 miles east of the north end of VS(14)23, the $35{\cdot}30^{o}/oo$ isohaline extends further south than on that section. The $35{\cdot}20^{o}/oo$ isohaline, on the other hand, is in opposite case; that is, the Atlantic influence is in reality felt further south on VS(14)23. Thermal conditions resemble those on the latter section in having for the most part a drop from over 12°C on the surface to 8°C at 50 metres while at F20c in the north the range is less than 4°C.

VS(14)26-28 are the three east-west sections derived from the July cruise.

Salinities exceeding $35{\cdot}30^{o}/oo$ appear on VS(14)26 only in the extreme west, but apart from the upper layers in the east, all the water on the section may be regarded as of modified Atlantic type. The low thermal range of C18d is in striking contrast to that for the east, where the surface exceeds 13°C and the bottom only 8°C.

As in the foregoing section, so in VS(14)27, the highest salinities occur in the west, but the Atlantic water passes east of the prime meridian only in the lower layers, fresh water, doubtless of Continental origin, occupying the upper layers.

On VS(14)28 the Atlantic water dwindles to a nucleus of over $35{\cdot}20^{o}/oo$ salinity in the lower layers of D15c and D15b. Scottish coastal water appears to be spreading out from the west and continental water encroaches from the east. Surface temperature is actually highest over the Atlantic water, which is for the most part in the zone of less than 8°C bottom temperature.

At none of the eight sections pertaining to the July cruise does a bottom temperature of less than 7°C occur, though the data extend into the central area where such cold water was found in July 1911 and 1913.

Doubtless the very high salinities found in the Northern North Sea, implying a powerful Atlantic influx, are related to this circumstance, the salt warm water being present in large enough volume to penetrate to the centre of the Northern North Sea and raise its temperature and salinity above the level found there in previous years.

HC(14)13-16 show on the usual four horizontal planes the hydrographic conditions met with on the July cruise.

While a similar lobe-formation to that in the second half of June exists in the isohalines of the north-west, important changes since that date are registered.

The 35·30°/oo water lies slightly further south at the surface and 20 metres, while at 50 and 100 metres a tongue of this highly saline water attains lat. 59°N. - 60 miles further south than in the latter part of June. The 35·20°/oo isohaline also occupies a more southerly position, particularly in the lower layers, where it has broadly the position of the 35·10°/oo isohaline in late June.

The 35·20°/oo and 35·30°/oo isohalines also bulge southwards (except in the surface layers which consist of fresh Continental water) between 1° and 2°E. This central saline area is separated from that in the west by a lobe of less than 35·10°/oo water which points north along 1°E.

This distribution of salinity is analagous to that found in July 1913, except that at that season the whole system lay 2° of latitude further north. The 120-mile difference of location is an index of the much greater extent of Atlantic water in the North Sea in July 1914 than in July 1913. The phenomenon of splitting of the Atlantic stream by relatively fresh water is found also in May and August 1911, and would therefore seem to be a normal feature. In 1912 the Atlantic stream lay entirely on the east side of the North Sea, a condition which may be regarded as an abnormally large developement of the eastern, and usually smaller, branch of the Atlantic influx.

Temperature in the North Sea, as shown on the charts, is highest in the south centre at the surface and 20 metres and diminishes westwards and northwards, though more rapidly in the former direction. At 50 and 100 metres, however, the gradient is reversed, higher temperatures occurring in the west. This distribution is similar to that found in summer in previous years and is due to the Atlantic water having a warmer bottom and cooler surface than that in the centre, whose bottom layers tend to retain their low spring temperatures and whose surface layers warm readily under solar heat. Both of these processes are due to the relatively slow circulation of the water in the centre of the Northern North Sea.

Latitude $57^{\circ}30'$N, or the 50 fathom contour, again figures on the charts as a hydrographic boundary. This line limits the Northern North Sea region; South of it, salinity and temperature, as shown also by the vertical sections, is irregular.

The separation hydrographically of the Northern and Middle North Sea is apparent also on the T-S diagram TS(14)4. The curves on this diagram fall into two distinct classes, one with salinity exceeding $34{\cdot}90^{\circ}/oo$ and the other with salinity below this value.

Within the former class, certain groupings of the curves may be distinguished. That representing water most recently derived from the Atlantic stream and therefore styled A, occurs between salinities of $35{\cdot}25^{\circ}/oo$ - $35{\cdot}35^{\circ}/oo$ and temperatures of $8{\cdot}5$-9°C. This is a bottom group mainly, but at the same time the upper parts of the curves cluster together and surface temperatures are 11-12°C.

Nearby is a group which is more distinctly a bottom type, with salinity $35{\cdot}25^{\circ}/oo$-$35{\cdot}35^{\circ}/oo$ and temperature $7{\cdot}5$-$7{\cdot}7^{\circ}$C.

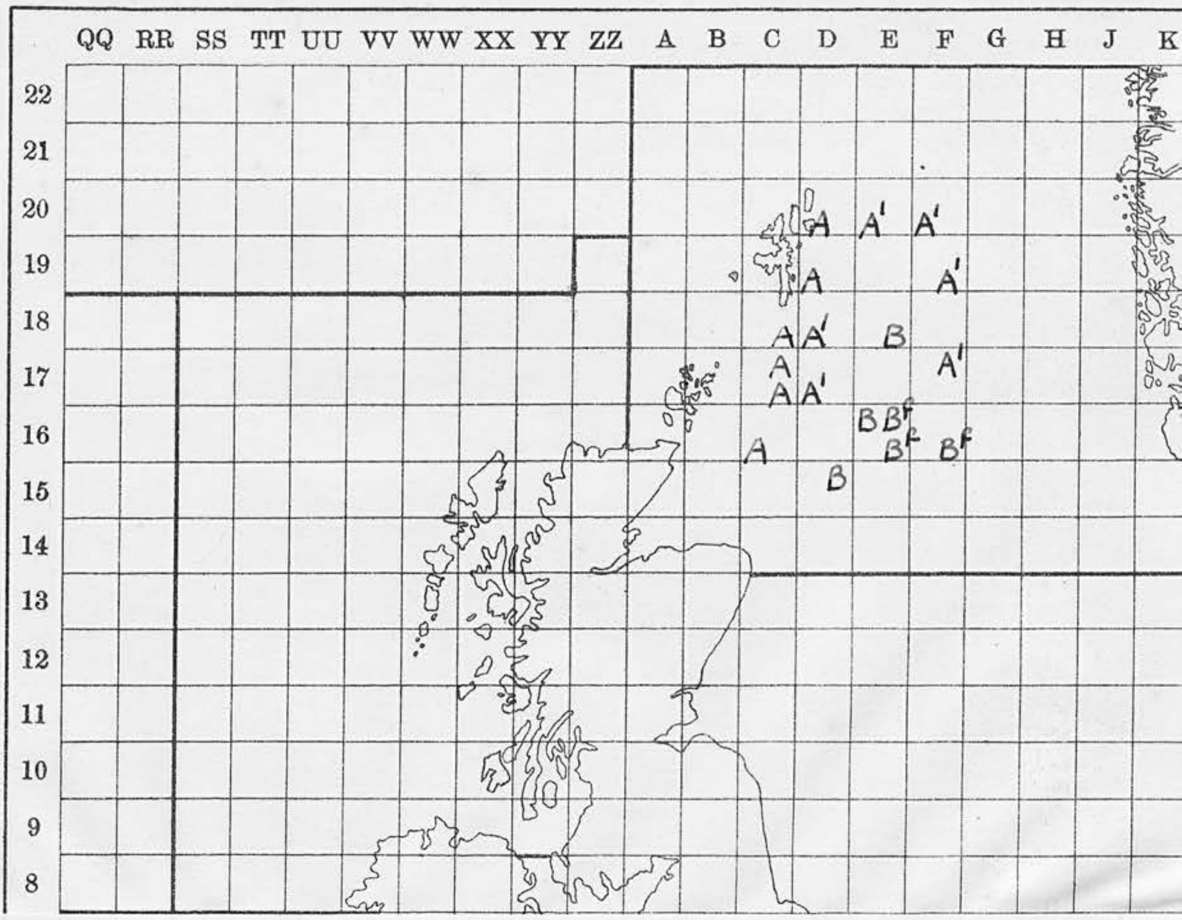


Figure 28.

Distribution of Water-Types, July 1914.

Salinity and temperature of the water-types shown on Figure 28, together with the positions and dates of the stations whose T-S curves make up the groupings which represent the above types.

TS(14)4

A

(35.25-.35 $^0/_{oo}$ x 8.5-9 ^{0}C)

4	C18d	6/7
5	C17b	6/7
6	C17d	6/7
7	C16c	4/7
18	D20c	8/7
19	D19c	11/7

A'

(35.25-.35 $^0/_{oo}$ x 7.5-7.75 ^{0}C)

20	D18c	14/7
21	D17c	14/7
25	E20c	8/7
31	F20c	8/7
32	F19d	9/7
33	F17b	10/7

B

(35.18-.30 $^0/_{oo}$ x 7-7.5 ^{0}C)

	22	D15b	15/7
	27	E18d	10/7
	28	E16a	14/7
f	29	E16b	14/7
f	30	E16d	15/7
f	34	F16d	15/7

This group is named A′. As in the early part of June, these two types differ in temperature rather than in salinity. Their positions on Figure 28 give a clue to the influence underlying the differing temperature conditions of the two types. The A water lies west of the A type: the former is in a zone where tidal mixing is active, the latter further offshore.

Supporting the above explanation of the distinction between A and A′ is the fact that there is a third bottom water type, B, on TS(14)4, which, with limits of 35·18°/oo-35·30°/oo x 7-7·5°C differs little from A′. The A′ type is almost a transitional type between A and B and is undoubtedly closely related to the latter. It may therefore be assumed that the Atlantic pulse is no longer active, though the highly saline water it brought into the North Sea is still present.

The conclusion is that the peak of the Atlantic pulse in the North Sea occurred between the second June cruise and the July cruise, for in the former the Atlantic water seemed to be in course of extending its influence, while in July it appeared rather to be spent and about to be assimilated into the North Sea water-complex.

SUMMARY OF HYDROGRAPHIC CONDITIONS in the NORTH SEA in 1914.

A superabundance of Atlantic water characterised the hydrography of the Northern North Sea during the period April - July of the year 1914.

The highly saline water entered the area in two main pulses, the first and greater in, or just prior to April and the second at the end of June and/or beginning of July.

The course pursued by these Atlantic influxes to the North Sea was that usually followed, namely across the Southern Norwegian Sea for some distance and thence to the east side of Shetland and so southwards. The lateral spread of the warm salt water was so great as to displace the cold bottom water normally found in the centre of the North Sea.

The volume and concentration of the Atlantic water in the North Sea in 1914 was greater even than in 1911, a year when the Atlantic influence was unusually large in the Faroe-Shetland Channel, so that it may reasonably be assumed that if the latter region had been visited in 1914 it would have been found to be particularly outstanding in respect of the amount of Atlantic water present. This supposition is borne out by the fact that at the few stations visited in this region in 1914, Atlantic water was more dominant than in 1911.

The Middle North Sea was not affected in the same way as the Northern North Sea, the boundary between the two regions being close to the 50 fathom contour. As in the three previous years, the Middle North Sea held water of irregularly-distributed low salinities.

FINAL SUMMARY

The hydrography of the Northern North Sea and its contiguous regions in the years 1911 to 1914, as far as these are covered by the Scottish and relevant foreign data, has been investigated in the previous pages. It now remains to summarize briefly the salient features common to the four years and to point out their individual characteristics.

The dominant factor in the water-economy of the region under survey is the Atlantic stream - the "Norwegian" branch of the North Atlantic Drift. This warm salt water, when it first enters the region, streams north-eastwards through the Faroe-Shetland Channel following the edge of the Scottish Continental Shelf.

According to Robertson (5), part or all of this water enters the North Sea by the Orkney-Shetland Channel. The grounds for such a view are difficult to discern in the data for the years 1903-1910: in the four years dealt with in the present investigation, no such movement takes place. Fresher water proceeding from the vicinity of the Butt of Lewis, however, probably does enter the North Sea from between Shetland and Orkney.

The volume of Atlantic water in the Faroe-Shetland Channel is not constant. In 1911, the amount was one of the largest recorded in spring since the inauguration of the Scottish hydrographical work in 1902. In 1912 and 1913, on the other hand, the Atlantic water was of less than usual bulk. The Channel was not traversed in 1914 but from the observations made off the north and west of Shetland and from conditions in the North Sea, it may safely be inferred that the volume of Atlantic water in the Faroe-Shetland Channel was quite extraordinarily large.

The usual mode of entry of the Atlantic stream into the North Sea is by way of the Southern Norwegian Sea. This movement is not, however, continuous, but rather in the form of a series of pulses. When only a small amount of Atlantic water is entering the North Sea, it swings directly round the North of Shetland, but when a more or less powerful influx is in progress the mode of entry is thus:-

The Atlantic water from the Faroe-Shetland Channel pursues its course along the edge of the Continental Shelf across the Southern Norwegian Sea to the spur of the Shelf at about 61°30'N., 1-2°E., where the part to enter the North Sea swings southwards and divides. The major portion recurves back on itself to pass to the east of Shetland, while the minor branch, in the bottom water-layers, maintains its southerly course, still on the edge of the Continental Shelf, which leads it into the east side of the North Sea.

During its transit of the Southern Norwegian Sea, the Atlantic water is diluted on its lower side by cold fresh bottom Norwegian Sea water and to a slight extent sometimes on the surface by fresh Continental water from the north-going stream on the west coast of Norway. The result is that the Atlantic water eventually reaching the North Sea differs somewhat from that in the Faroe-Shetland Channel.

An incursion of such nature by the Atlantic water is nowhere suggested in the reports for the years 1902-1910, but the close examination of the data for the period 1911-1914 has shown that the Atlantic water does indeed pursue such a devious course.

The Atlantic influx to the North Sea generally occupies the north-western area, between Shetland and Aberdeen, but here again the degree of Atlantic influence varies. In respect of yearly periods, the influx was in greatest bulk over the longest period and reached furthest south in 1914. Second place was taken by 1911, while in 1912 and 1913 Atlantic influence was comparatively meagre.

The first Atlantic influx in the year 1911 occurred in May and was followed by an even greater pulse in August.

In 1912 the Atlantic water found its way to an unusual situation - the east side of the Northern North Sea - while the north-western area was relatively free from Atlantic influence.

One feeble incursion of Atlantic water occurred in 1913, in July.

The year 1914, like 1911, witnessed two distinct pulses of the Atlantic stream. The first, just prior to April, was the minor, succeeded by a much more powerful influx, greatly exceeding any in 1911, in the end of June and/or beginning of July.

The narrow zone west of the Atlantic water in the Northern North Sea is generally occupied, especially in the upper layers, by fresher water originating either in the Moray Firth or the north-west coast. Tidal mixing reduces the vertical gradient of both temperature and salinity.

East of the Atlantic stream, the water in the centre of the Northern North Sea is relatively quiescent, what movement there is being mainly a gyratory one of the mass as a whole. Salinity is rarely high and usually fairly uniform. While bottom temperatures remain low throughout the year, surface temperatures reach in summer a maximum for the year. In the same season, fresh Continental water spreads westwards on the surface from the Norwegian Coast to varying extent in different years. The greatest expansion took place in 1913.

The Atlantic water in the modified form found in the north-western area does not penetrate to the Middle North Sea. The 50-fathom contourlimiting the Northern North Sea plateau on the south is also to a very large extent a hydrographic boundary. South of this line, in the shallower Middle North Sea, the Atlantic influx is felt only indirectly and salinity generally is low and irregularly distributed.

Fresh coastal water encroaches on the surface from both sides in the summer months.

The hydrography of the Northern North Sea and its adjacent areas is to a large extent controlled by the same factors in successive years. The relative importance of these factors, however, is not constant and it is this variation which constitutes the individuality of any single year. Further hydrographic research on the area, utilising temperature and salinity data, will therefore probably be most profitably directed towards an investigation of yearly characteristics and at the same time to an amplification of the present knowledge of the constituent hydrographic factors rather than towards an attempt to formulate a statement of "normal" conditions, the significance of which would be vitiated by the importance of the yearly fluctuations in hydrographic conditions.

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